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TURBINE ENGINE COMPOSITE PREFORMS: DESIGN OF MAGNAWEAVE LOOM FOR 3-D BRAIDING NET SHAPES

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August 1991

Final Report for Period July 1988 - December 1988

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3-D braiding technology should fabricate integrally braided preforms for turbine engine parts. Using MAGNASWIRL technology, a circular 3D braiding machine design was proposed. Design requirements were defined in terms of anticipated performance requirements for a turbine rotor. Preliminary designs were generated for a 30-ring, 360 slot/ring MAGNASWIRL machine, capable of fabricating preforms for (1) test discs, (2) 2- or 4-bladed discs, (3) 36 bladed discs. Silicon carbide (continuous filament) was the fiber of design. Loom loadings were developed to provide continuous and constant fiber volume; machine motion sequences were developed for integrally fabricating body and blades.

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This technical report has been reviewed and is approved for publication.

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SUMMARY

Phase I of the project investigated the feasibility of adapting the 3-D braiding process, MAGNAWEAVE, to fabricate preforms for ceramic composite shapes that would meet Air Force Propulsion Laboratory requirements for gas turbine engine components.

The shape of prime interest was found to be the multi-bladed turbine rotor. Desired directional mechanical properties were identified, which established a set of criteria for evaluation of the loom design and weave geometries to be developed. Candidate fibers and acceptable levels of fiber volume were identified to complete the requirements.

Initial conceptual designs were developed into a model involving several rings in a circular adaptation of MAGNAWEAVE which is designated MAGNASWIRL. 360 element rings were selected for maximum flexibility in shape and dimension of the preforms. Standard MAGNAWEAVE techniques were used to determine weave geometries to meet the requirements. These weave geometries, together with fiber specifications, determined the number of rings and the ring and spoke motion across the machine.

Loom loading patterns were developed to maintain a fiber volume that varied minimally across the radius of the preform. Loom motion sequences were established to produce the preforms to meet the requirements.

In evolving the final design concept, the study addressed a succession of shapes which increased in complexity, and demonstrated the validity of the approach. Thus, loom loadings and motion sequences were developed for (1) thick-walled discs; (2) 36-finned discs; (3) 36-finned discs with progressive insertion of additional fibers; and (4) 36-bladed rotors, where using two different fiber sizes permits thinner blades.

The Phase II project objective is to design and build a MAGNASWIRL loom and to produce a small number of rotor-shaped preforms to be made available for matrix insertion and testing. For the Phase I machine design effort the generic rotor shape used to specify loading and motion requirements was the 36-finned disc with progressive insertion.

The machine design activity developed preliminary designs for a circular machine to meet the loading and motion requirements for the selected shape. Drawings detailing these concepts were generated and used for costing efforts for the Phase II project.

The inherent flexibility of the MAGNASWIRL machine technology will permit its utilization for a broad range of turbine engine components. However, flexibility has been sacrificed in the Phase I machine design to keep the costs within the scope of a Phase II project.

The feasibility of meeting the program's objectives has been demonstrated in the Phase I effort. A Phase II project will deliver generic turbine rotor shape preforms of SiC to the Air Force. Matrix insertion techniques already developed can be employed to make the final composite shapes for testing; discussions with the major producers of silicon carbide composites have been initiated.

Commitment to carry the technology into Phase III is identified, contingent on the success of the Phase II effort and the return on investment to commercialize the technology. Early market discussions elicit favorable estimates.

Based on the success of Phase I, a Phase II proposal has been submitted (December 28, 1988). Much of this report is embodied in that proposal.

TABLE OF CONTENTS

FIGURES

TABLES

I. Introduction

This SBIR project addresses the issue postulated in the solicitation 88-1.[1]

> "Continuous fiber reinforced composite materials offer properties which enable the designers of gas turbine engines the ability to develop light weight, high performance engine components...Investigate the application of special...braiding techniques to the automation of the fabrication of composite components for advanced engines. Current fabrication methods, ...rely heavily on hand layup techniques. This leads not only to high fabrication costs, but also to problems with repeatability and quality assurance. Future, highly structurally efficient components will make very high demands on fiber orientation accuracy and integrity."(1)

This succinct analysis has, at once, defined the problem, identified the objective, and offered a possible solution to the problem. Further, it has established the criteria by which the adequacy of a solution shall be judged.

The Phase I proposal[2] of this project expanded on these requirements, and offered evidence that the continuous, automated 3-D braiding process, MAGNAWEAVE, had the potential to satisfy these criteria. In doing so, this process would establish a viable fabrication technology for these complex shapes which must operate under extreme conditions, and would

MAGNAWEAVE is a trademark of Braidtech, Inc.

expand the opportunity of the designer to exploit concepts which demand sophisticated, and reliable, fabrication techniques.

We believe the effort conducted under Phase I of this project has achieved its objectives. In short, it has established the potential of the MAGNAWEAVE process, suitably modified, to meet the following criteria:

1. Generate a continuous filament preform with extreme accuracy of fiber placement.

2. Fabricate integrally braided preforms for extremely complex shapes.

3. Define a fabrication technology with the flexibility to order braid geometry to meet various structural load requirements dictated by the design.

4. Identify a manufacturing technology with the capability to fabricate varied shapes with a single machine, whose flexibility of motion and fiber orientation makes for exceptional versatility.

II. Background

A. Candidate Shapes

A desirable goal for a Phase II machine would be the versatility to make preforms for more than one gas turbine engine part. The discussions and literature search included identifying a variety of shapes of interest to turbine engine designers, and determining if a machine design could possess the flexibility to manufacture preforms for those shapes.

Of prime interest in all the discussions was the gas turbine rotor. Table I lists several candidates.

TABLE I

Candidate Shapes for Phase II

Axial Turbine Rotor
Radial Flow Turbine Rotor
Mixed Flow Compressor
Insertable Vanes for Turbine Nozzle
Combuster Liner
Air Foil

Of this list, by far the most valuable to the industry is the axial turbine rotor. Consequently, this shape has been chosen as the prime candidate for the Phase II effort.

Of the rest, the other rotors appear as variations in the axial rotor, more complex in geometry, but, evidently,

fabricable with the MAGNASWIRL machine to be designed here.

The air foil cross section has already been fabricated as a 3-D braid in an evaluation program conducted by Cumagna Corporation for Ex-Cell-O of Walled Lake, Michigan. The configuration is achieved by step-wise loading of a Cartesian (rectangular) braider, as shown in Figure 8 in Appendix D. (It should be noted that identical weave geometries can be achieved on MAGNAWEAVE (Cartesian) and MAGNASWIRL machines. Rows in a MAGNAWEAVE machine correspond to rings in a MAGNASWIRL unit; the columns on MAGNAWEAVE correspond to the spokes of a MAGNASWIRL.) One expects to fabricate air foil shapes by loading a segment of the MAGNASWIRL, and considering that segment as a Cartesian machine.

A MAGNASWIRL of the capacity proposed for Phase II will have the capability to fabricate those shapes which are likely to be useful in a turbine rotor development program. The table below lists representative shapes.

TABLE II

Shapes for Gas Turbine Development Programs

Solid Discs

Axially-holed Discs

Finned Discs

Thick and Thin Walled Pipe

Flanged Pipe

B. Turbine Engine Design and Fabrication

The gas turbine engine has evolved over the past years to become an efficient means of providing power. If one maximizes the speed of rotation and the operating temperature, and optimizes the geometric design, then maximum operating efficiency results. In propulsion terms, this maximum operating efficiency results in maximum efficiency in converting fuel to power. In missile and aircraft systems, this maximizing efficiency translates into extending the range of operation, or, alternatively, maximizing payload weight.[3]

These systems objectives distill into a short list of requirements:

1. Provide a material that will perform under the extreme conditions imposed by the design and operation of the gas turbine engine.
2. Provide capability to manufacture this design in a cost efficient manner.

During Phase I, discussions with various turbine engine designers[4,5,6], reviews of analytic and experimental studies defined the "desirable" and the "required" properties of a material of choice. Further, the materials components of a refractory composite were identified.

The list of properties of interest appear below.

Blade Section:	High radial strength Good circumferential strength Good axial strength High flexural strength High radial, high hoop shear
Disc section	High hoop tensile strength High radial tensile strength Good hoop shear strength

The comprehensive listing appears in Table III from a Garrett Publication [6].

During Phase I, discussion with representatives of Garrett[5], Williams International[4], and the Air Force Propulsion Laboratory focused on the desirable capabilities of a fabrication process that could respond, with minimum change, to evolving design changes. In a sense, the fabrication development was proceeding apace with the design effort, rather than acting as a "tandem operation" This approach has the advantage of shortening the period between concept and manufacture; it promotes interchanges between process developer and designer, in that each can reinforce his approach with some cross fertilization of what is feasible, desirable, or possible. The process developer will always take the position that simultaneous design and process development programs should occur side-by-side, in time. A better, more realistic solution gets to the use point faster.

TABLE III

Material Evaluations

A: Test Specimens:

w/ Fiber Architecture * Representative of:	Stress State of Interest:	Test Description:
• Airfoil Area	Radial Tension	Uniaxial Tension
	Chord-wise Bending	Flexural
	Chord-wise Shear	Double Notch Shear
	Radial Shear	Double Notch Shear
• Disk Area	Hoop Tension	Uniaxial Tension
	Radial Tension	Uniaxial Tension
	Shear	Double Notch Shear
• Blade-Disk Interface Area	Radial Tension	Notched Uniaxial Tension

B: Subelements (quasi-bladed disk or lawnmower blades):

Cold Spin Pit Test

* Assumes specimens to be machined from panels simulating fiber volume fraction and orientation. Panel architecture may be simplified (e.g. use rectangular weave to simulate polar weave on a unit cell basis).

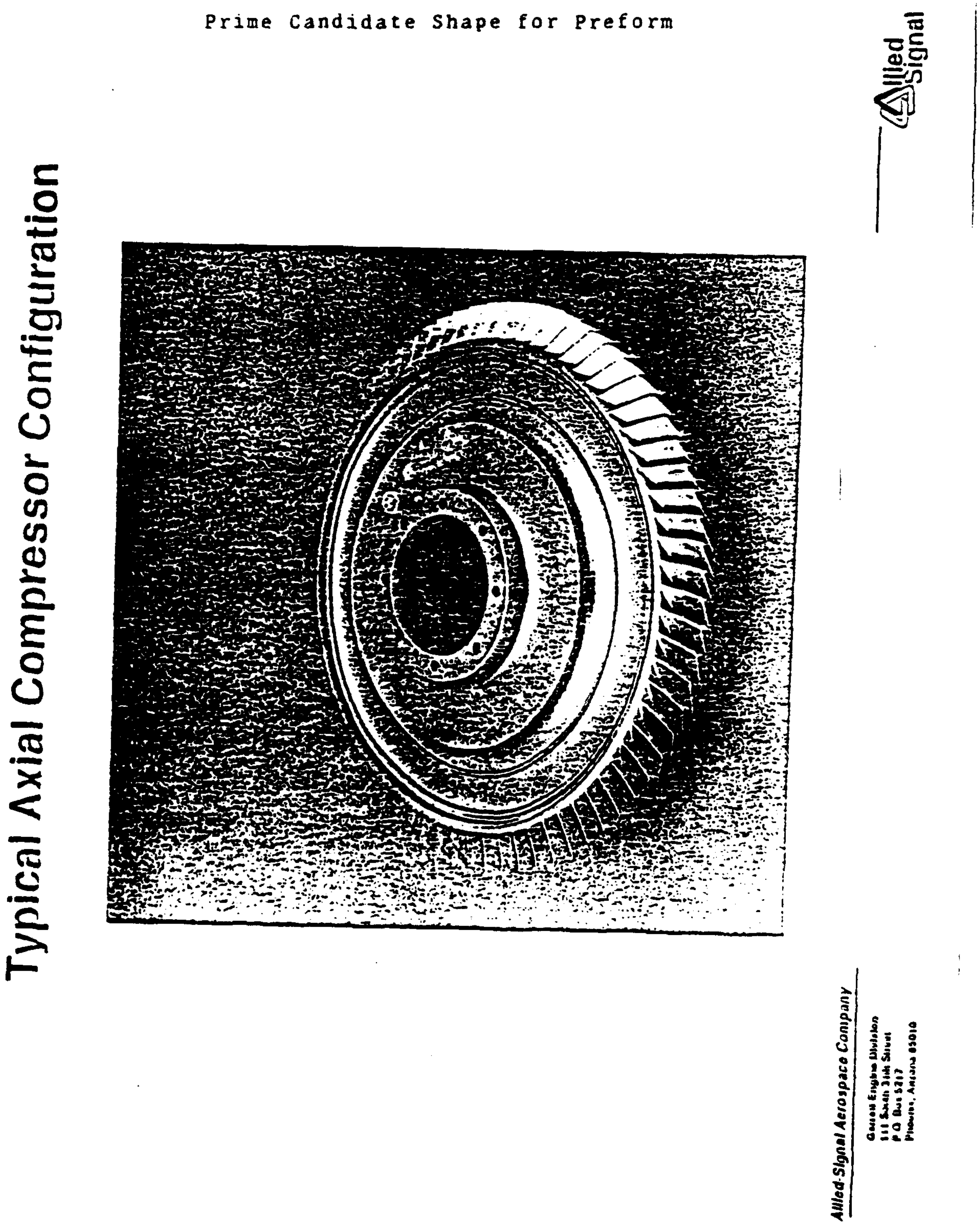
These, then, are the aspects of a manufacturing process that parts designers would like to have at their disposal:

1. Preforms with 3-D fiber reinforcement.
2. A process with excellent control of fiber placement.
3. A process capable of changes in fiber placement, to reflect changes in design.
4. Integrally formed preforms that eliminate attachment problems.
5. Stronger material in selected directions.
6. Reproducibility of fiber placement (excellent quality control).
7. Technology capable of fabricating complex shapes.
8. The capability to vary shape dimensions.
9. A single preform fabricating machine which would be capable of making preforms of more than one part; the more versatility, the better the investment.

The turbine rotor of a gas turbine engine emerged as the prime candidate for fabrication. The overriding interest of the propulsion community appears to be a representative shape depicted in Figure I[4]. The shape is a disc of 4 to 6 inch diameter, from which protrude at least 36 blades, evenly spaced around the perimeter of the disc, but canted, and of air foil shape of indeterminate (at this time) dimension.

Figure I

Prime Candidate Shape for Preform



C. The MAGNAWEAVE Process and Turbine Rotor Preforms

The Phase I project considered the following requirements for properties, shape, dimensions, and performance as imposed on the manufacturing process by the design objectives of the gas turbine wheel:

1. The machine should be capable of fabricating a variety of preform shapes.

2. The preforms will have a fiber placement (weave geometry) that can meet the structural requirements in all directions efficiently.

3. The weave geometry must be capable of wide and diverse fiber orientations, as dictated by the dimensions and the shape of the part, and the specific loads imposed.

4. Near net shaped preforms must be fabricable, to minimize distortion of the weave geometry during subsequent processing into composite.

5. The process must be automated, to insure high quality and reproducibility of fiber placement, and to operate as a low cost fabricating process for preform shapes.

6. It must be capable of producing high fiber volume preforms, as dictated by processing into composite, and design requirements.

7. It must be efficient in use of raw material.

8. It should be capable of fabricating complex, integrally woven preforms, eliminating need for attachments.

9. It must be capable of handling high modulus, and brittle fibers, with minimal damage, as a continuous process, rapid and economical.

It is evident that the MAGNAWEAVE process[7], and its circular counterpart, MAGNASWIRL[8], have embodied in its basic performance parameters the flexibility and the capability to provide the fabrication capability required, or desired, for a product line of gas turbine engine components.

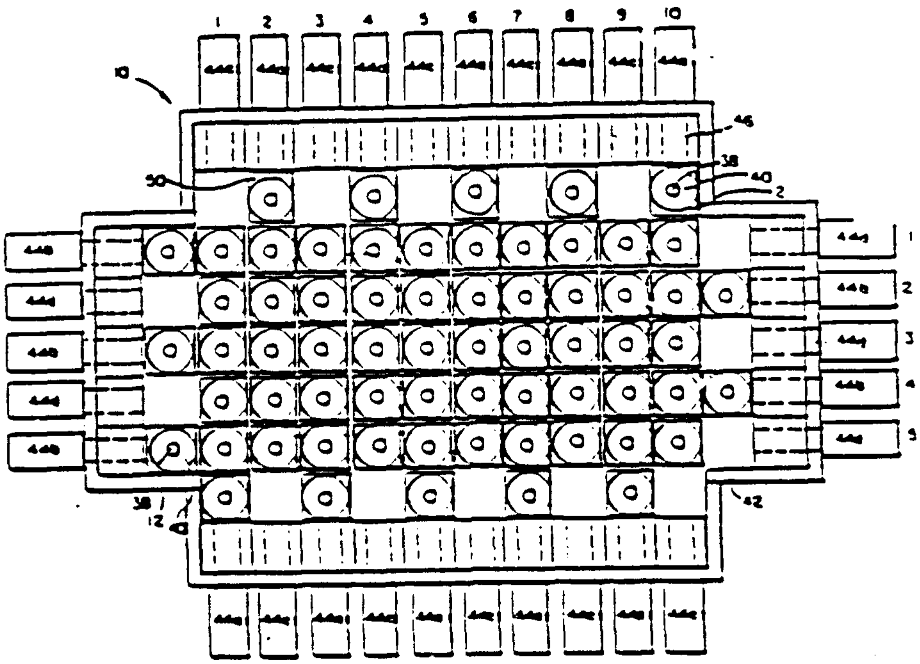


FIGURE 1. Loom Schematic

Figure II MAGNAWEAVE Cartesian Loom, Detail (USP 4,312,261)

Put in the simplest terms, MAGNAWEAVE is a three dimensional braiding process, where a machine is loaded in a specified manner with elements carrying approximately one pound of yarn each into a system which moves the elements in a regular fashion around and past each other to form a braid of a desired cross section. The shape of the part is determined by the loading

scheme, where the part width is determined by the number of filled elements in a row (Figure II), the height by the number of rows stacked above each other, and the shape by the arrangement of the active elements in the machine. The individual fibers are gathered above the loom bed, and carried off by a take-up whose speed is synchronized with the braiding speed in the body of the machine. The fibers are moved past each other, first in rows and then in columns perpendicular to the rows, forming the braided preform in the shape and net size of the preform desired.

The fiber orientation is determined by the manipulation of the motion of the elements, first by row, then by column, with the repeat distance (the distance separating successive braids) determined by the loom-braid point distance. What results is a preform to net shape. Further, as a result of the machine manipulation, the fibers in the preform have an orientation such that the vectors in the orthogonal direction meet the requirements for the properties established by the design. Figure III demonstrates the relation of vector component of strength to the loom motion.

The "weave geometry" is a term used to describe the angles the fibers make with the orthogonal axes. Ko [9] uses what I called the "straight stick" model to predict properties as the vector component of the fiber strength in the direction measured. Figure III demonstrates that the fiber direction is a

Figure III

"Vector Component" Model for MAGNAWEAVE" (Ko)

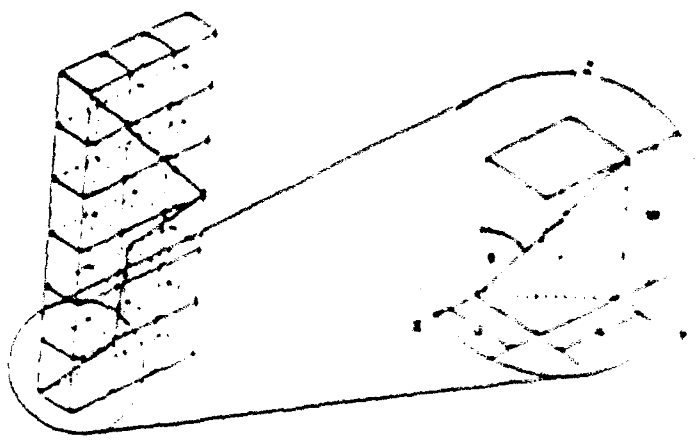
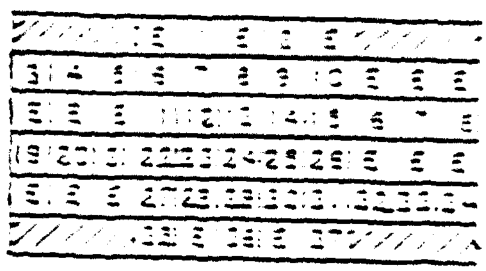


Figure IV

Loom Loading for 3 x 1 x 1 Weave



vector sum of three motions, x, y, and z, where x is the number of spaces moved in the y direction, and z is the distance separating successive weaves. A weave of 1 x 1 x 1 is isotropic, with fiber angle of 45 degrees to all axes. 1 x 1 x 3 has a more axially directed fiber; 3 x 1 x 1 is shown in Figure IV, with transverse orientation.

D. The MAGNASWIRL Process

The MAGNASWIRL loom is simple in construction and in operation, but versatile in capability. The bed of the machine consists of a number of concentric rings. Each ring is slotted at regular intervals to hold the yarn elements that are moved in the weaving process. The slots are radially cut, and their number is determined by the circumference of the part desired, using the fiber size desired. The number of rings is determined by the wall thickness of the part required. The outer rings may have twice the number of slots of the inner rings to maintain a uniform yarn density.

In operation, the rings are aligned so that the slots form spokes. The loom is loaded with yarn by inserting a yarn holder in each slot and connecting the length of yarn to a corresponding pin in a stationary plate at the top of the loom. A mandrel is installed in the inner ring of the looms, against which to weave.

Weaving consists of three basic motions:

1. Ring Motions - Adjacent rings move in opposite directions; a single ring motion consists of moving half the rings clockwise a number of degrees (correspond to the relative position of the slots), the other half moves counter-clockwise the same number of degrees. This forms the same number of spokes, but the slots inhabiting a given spoke is different.

2. Spoke motion - The yarn elements are pushed, across the rings, to comparable positions in adjacent rings. Neighboring spokes are pushed in opposite directions.

3. Combing - A comb is inserted between the spoke and raised to the stationary plate; the weave forms against the mandrel.

Repetition of these motions generates the preform.

Figure V and VI illustrate various yarn motions.

It is evident even it its simplest mode, that yarn moves from outer wall to inner wall, around the part, as it progresses from the top to the bottom of the woven part. (This description reveals that the process is truly a "braiding" operation - there are no yarns perpendicular to the direction of weaving. It is unlike tubular braiding in its complete flexibility in fiber orientation and complexity of shape formation).

Figure V

MAGNASWIRL Yarn Motion

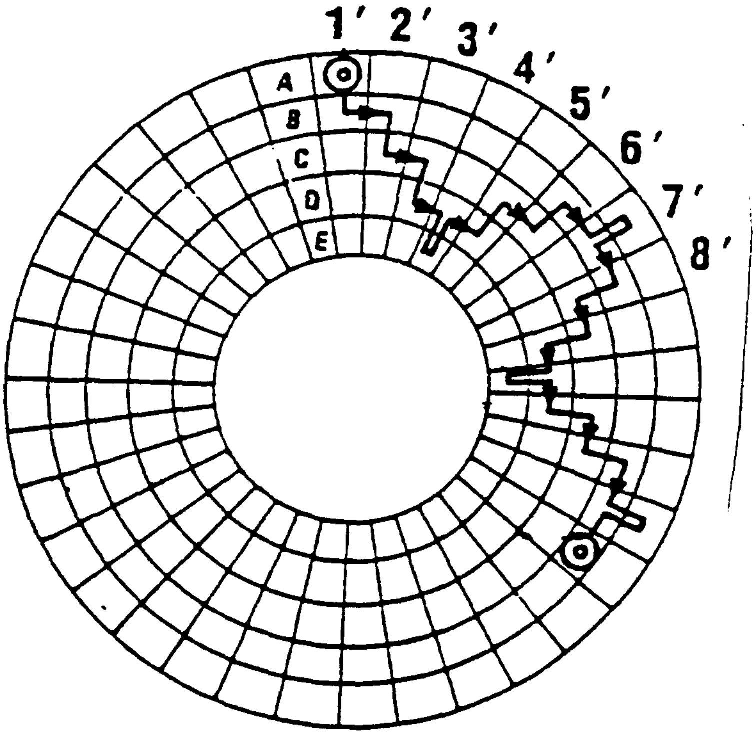
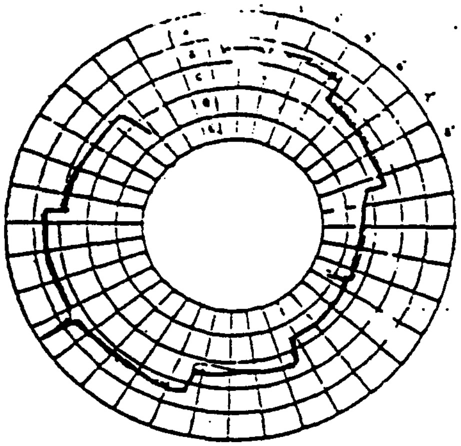
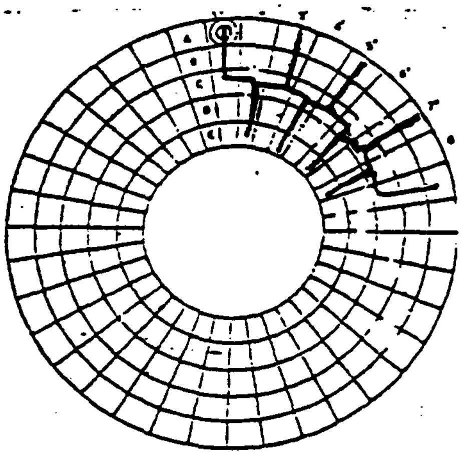


Figure VI

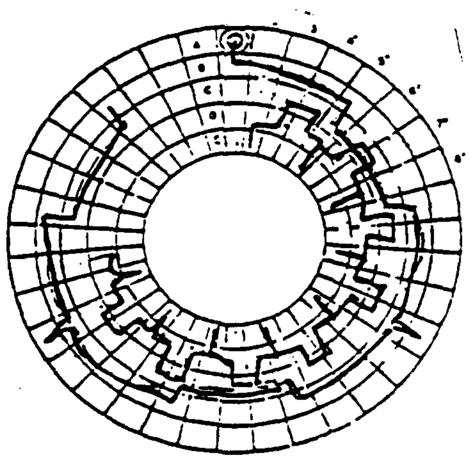
Various Yarn Motions



- HOOP ORIENTATION PREDOMINATES



- RADIAL ORIENTATION PREDOMINATES



- BI-"LAYER" MOTION

III. Turbine Rotor Performance Requirements

At this point the discussions mentioned earlier have resulted in a consensus on the material and structural properties necessary to meet initial turbine rotor requirements.

A. Fiber of Choice: Nicalon Silicon Carbide Fiber

This product is currently supplied by Dow Corning Corporation, by importing the fibers from Nippon Carbon Co. Ltd. of Japan.[10] It is a strong, tough fiber, with excellent high temperature mechanical properties. We reproduce here the relevant characteristics:

TABLE IV

Properties of Nicalon

Property	Ceramic Nicalon	HVR Nicalon
Tensile Strength (ksi)	375	340
Tensile Modulus (msi)	27	27
Density (g/cm3)	2.50-2.65	2.30-2.40
Tex (g/100 m)	210 - 10	210 - 10

B. Fiber Bundle Size

The fiber is provided as 500 filament fibers; it can also be purchased as multiples of 500, namely 1,000 or 2,000 filaments/tow.

Data is not available to the writer about the variation, if any, of properties of the composite as a function of bundle

size. If experience with polymer composites is duplicated, tow size has no effect on mechanical properties; if anything the properties increase with increasing tow size. This works to simplify the machine by minimizing the number of elements to be loaded into a machine for a given part size.

C. Fiber Volume

To date, other composite processing studies have found, as expected, that a lower fiber volume makes it easier to deposit a uniform matrix in the preform with a minimum of voids. Larger fiber volumes will permit smaller part dimensions.

Early experience braiding Nicalon[6] showed that a dense fiber volume is achievable with Nicalon; how easy that fiber volume is to infiltrate has not been established.

The limits of fiber volume appear to be:

$$V_f\text{: from } 0.25 \text{ to } 0.40$$

D. Directional Mechanical Properties

Standard practice for the 3-D braider is to accept from the parts designer a list of mechanical properties as a function of direction -- hoop, axial, and radial strength, for instance. For a given range of part sizes, the material developer would determine the fiber volume to be used, with a selected fiber, in a selected matrix, with a selected weave geometry.

The following table summarizes the recommended performance characteristics as distilled from our discussions with turbine designers.

TABLE V

Turbine Rotor Design Characteristics

1.	Shape:	Round disc, with blades (canted) sticking from the outer edge of the disc
2.	Dimensions:	I.D.: 1.0" to 1.5" O.D.: 5.5" to 8.0" Blades: about 36 Blade Dimensions: 0.75" long Blade shape: wedge, fin, air foil Disc thickness: 1.00" to 1.25"

A representative shape has been provided by Halada of Williams International, and other shapes including air foils, vane segments, etc., are to be found in Appendix D.

Halada has also provided, in qualitative form, a list of desired characteristics, as summarized in Table VI.

Table VI

Turbine Rotor Design Objectives

Section	Property	Level Desired
Bore	hoops strength	high
Blade roots	radial strength	high
Rotor blades	woven structure	closely woven

Draskovitch (Garrett) has provided a rather detailed analysis of desired properties and configurations in an RFP for the "High Mach Nonmetallic Turbine Engine Evaluation", sponsored by the Propulsion Laboratory[6]. Specifics emerge from this PRDA:

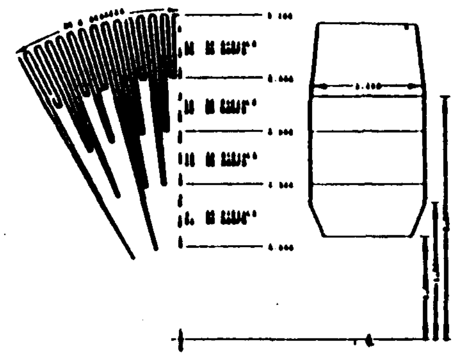
Bore	Hoop strength	20 to 50 ksi
	Radial strength	10 ksi
Blade	Hoop strength	20 ksi
	Radial strength	10 ksi

The PRDA goes further, and describes a Mixed Flow design (Figure 4, Appendix D), which would require tailored fiber architecture. A stress pattern is provided (Figure VII) showing 35 ksi max stress, and a blade with max stress of 61 ksi.

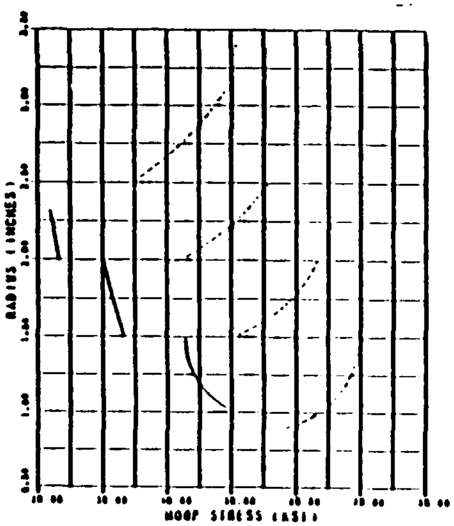
Figure VII

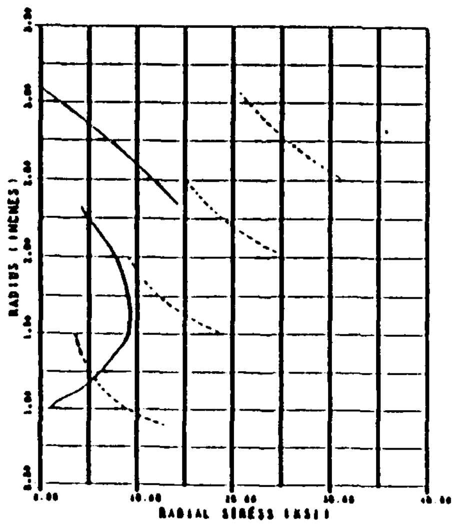
Loads Definition, Directional

Disk Stresses May Require Tailored Fiber Architectures



Example of Polar Weave Used in Axial Disk





---- Calculated Strength

—— Calculated Stress

ρ = 1.66 g/cc (0.06 lbm/cu.in.

Stresses are proportional to density

Allied-Signal Aerospace Company

Garrett Engine Division
111 South 34th Street
P.O. Box 5217
Phoenix, Arizona 85010

Allied Signal

IV. Determination of Machine Design Requirements

The candidate part of choice is represented in Figure VIII, as provided by Halada of Williams International. It is an axial turbine rotor with 36 blades. Its dimensions are as shown.

Using this part as a "generalized model", an analysis was conducted to generate the design requirements for a machine capable of fabricating such a shape. Design criteria included flexibility in ordering fiber placement, control of fiber volume, and efficient machine manipulation.

A. Sizing the Loom

The candidate part, shown in Figure VIII consists of a disc with a hollow center and a number of fins protruding from its edge. For design purposes, 36 blades are considered.

As an exercise, one selects a loom geometry that contains 360 elements in the outer rings -- those which will form the blades. A number of factors dictate this choice:

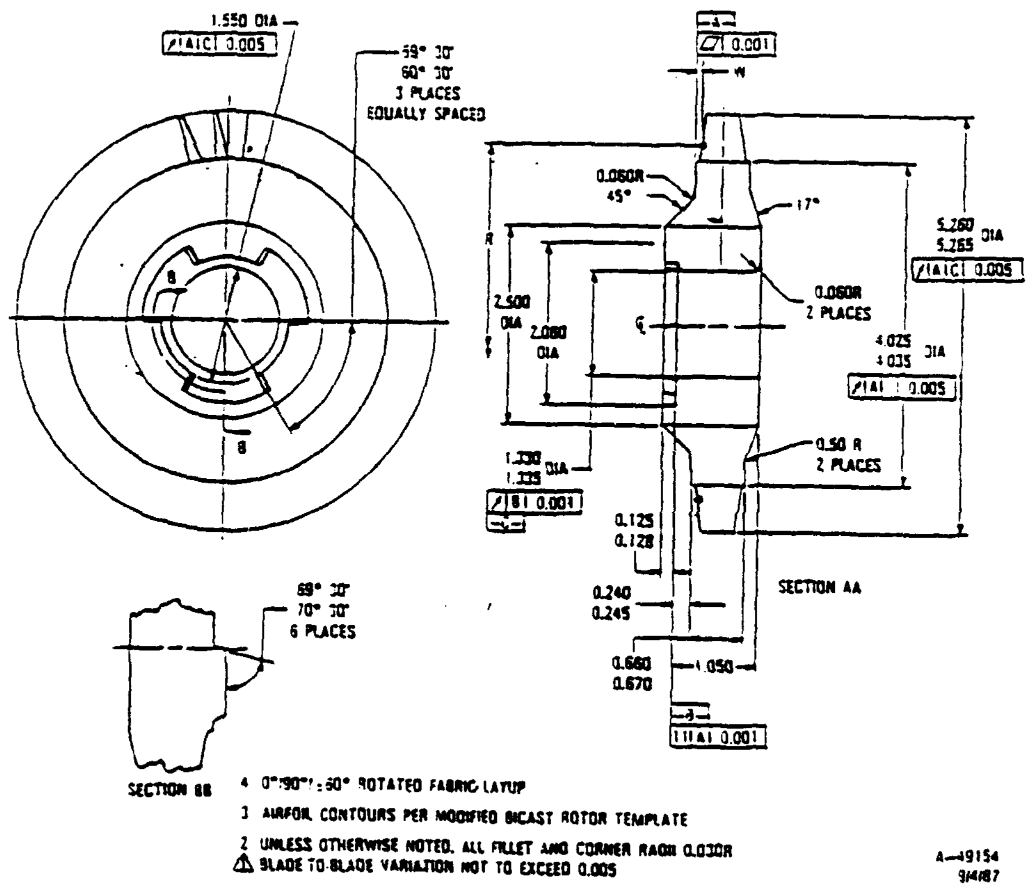
1. A blade will be formed every ten degrees around the disc's circumference.
2. Since the number of elements being filled in subsequent rings will be less, and be a fraction of the outer rings, the fact that the number 360 contains a large number of factors, namely: 2, 2, 2, 3, 3, 5 means that a large number of

Figure VIII

Prime Candidate Turbine Wheel Dimensions

AIRFOIL DATA

SECTION	RADIUS	W ⚠ ±0.01
A A	2.016	0.050
B B	2.156	0.055
C C	2.296	0.060
D D	2.437	0.075
E E	2.577	0.090
F F	2.717	0.13



WR24-7 Ceramic Composite Rotor Design Drawing.

combinations can be invoked, if desired, for the operation of the loom. That is to say, looms which have the ratios:

360 to 180 to 90 to 45 to 15 to 5,

or 360 to 120 to 60 to 30 to 15,

or 360 to 90 to 45 to 15 to 5,

or 360 to 60 to 30 to 15 to 5,

or 360 to 40 to 20 to 10 to 5

or 360 to 180 to 60 to 30 to 10 to 5,

or 360 to 180 to 60 to 20 to 10 to 5,

or 360 to 180 to 45 to 15 to 5,

or 360 to 180 to 60 to 20 to 5

or a large additional number of combinations would be workable with the 360 element loom.

It can be seen that not only the outer rings (making the blades) but all the subsequent rings should contain 360 elements, as well. In that fashion, all these combinations are candidates for loom loading. The machine will have a maximum versatility.

Yet a third consideration dictates the 360 element/ring for all rings. The slots in the inner rings, which will not carry active elements, will carry blanks. The spoke movement can be easily effected, in any spoke, if the rings are all filled, whether they participate in the braiding or not. The standard technique of effecting spoke motion by forcing elements across the rings can be employed. This places the actuating mechanisms for the spoke motion along the interior rings, as is usual and standard with cartesian (rectangular) looms.

B. Composite Characteristics

Fiber volumes from 0.25 to 0.40 have been reported for Nicalon reinforced silicon carbide composites. Although little infiltration (CVD) work has been done with 3-D braid, a fiber volume of 0.4 will be the design target here, and the subsequent calculations are made on that basis. For MAGNAWEAVE a fiber volume of 0.4 presents no problems, we believe. Earlier, the CUMAGNA Corporation, predecessor of Braidtech, braided some Nicalon for United Technologies as a flat panel; as a demonstration for Naval Surface Weapons Center, CUMAGNA fabricated thicker panel pieces and some square rods of very high fiber volume. The comment then, after the fact, was that it was probably too dense to infiltrate. Lower fiber volumes are always possible, and ease the problem of fabrication.

Data available from AMERCOM is shown in Appendix E for a SiC/SiC 3-D braided composite.

With a fiber volume of 0.4, and the properties of the Nicalon presented above, the "straight stick" model would predict axial, circumferential, and radial tensile strengths.

It is necessary to define a weave geometry for such a prediction. We chose as an example the following loom motion:

1 x 3 x 1, which means that we move the rings one spoke

clockwise or counterclockwise, depending on the overall loom motion sequence, then move the spoke elements across three rings either inward or outward, again, depending on the loom motion sequence. The braid repeat will be the width of the individual fiber, compensated for the fiber volume.

This loom motion produces a "flat braid", with much radial vector component.

The tensile prediction straight stick are

Axial Tensile Strength 45.1 ksi

Radial Tensile Strength 135.5 ksi

Circumferential Tensile Strength 45.1 ksi

These predictions do not take into account any contribution by the matrix.

C. <u>Predictions of Properties - Techniques Available</u>

Chou of the University of Delaware has conducted a sophisticated modeling for 3-D braided MAGNAWEAVE, and uses these relationships to predict:

(1) <u>Elastic Stiffness</u>

$$E_x = \frac{1}{P_b P_c V_{fx}} \left(\frac{4P_1}{L_c \theta_1} + \frac{4P_1}{L_b \theta_1} \right)$$

$$E_y = \frac{1}{P_a P_c V_{fy}} \left(\frac{4P_2}{L_a \theta_2} + \frac{4P_2}{L_c \theta_2} \right)$$

$$E_z = \frac{1}{P_a P_b V_{fz}} \left(\frac{4P_3}{L_b \theta_3} + \frac{4P_3}{L_a \theta_3} \right)$$

(2) Poisson's Ratio

$$\nu_{12} = -\frac{\epsilon_2}{\epsilon_1} = \left[\frac{4P_a}{\ell_c\ \theta_1}\right] \Big/ \left[\frac{4P_b}{U_2}\right]$$

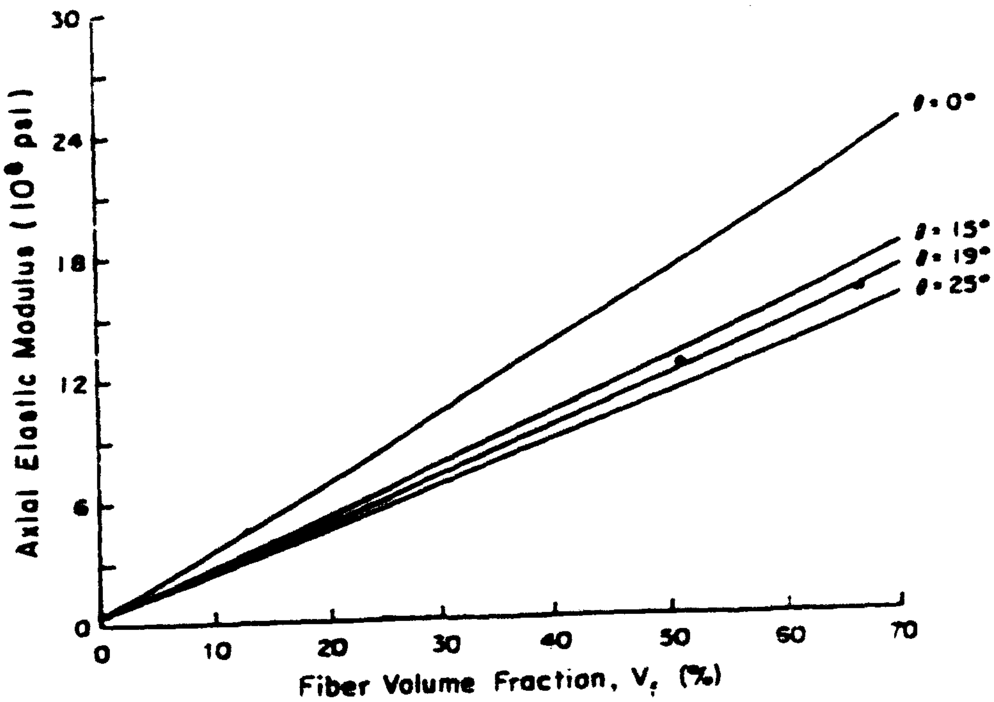
$$\nu_{23} = -\frac{\epsilon_3}{\epsilon_2} = \left[\frac{4P_b}{\ell_a\ \theta_2}\right] \Big/ \left[\frac{4P_c}{U_3}\right]$$

$$\nu_{31} = -\frac{\epsilon_1}{\epsilon_3} = \left[\frac{4P_c}{\ell_b\ \theta_3}\right] \Big/ \left[\frac{4P_a}{U_1}\right]$$

(3) Elastic Modulus

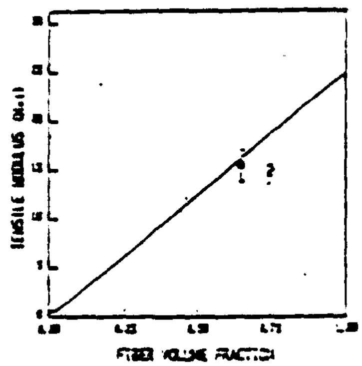
Predictions of Elastic Modulus for composite MAGNAWEAVES show excellent agreement with measured values, as the graph below, showing behavior vs. predictions for Graphite/Epoxy MAGNAWEAVE composites.

Figure IX



Ko, in an independent study shows excellent agreement between predictions of elastic modulus and measured values for graphite epoxy MAGNAWEAVE composites.

Figure X

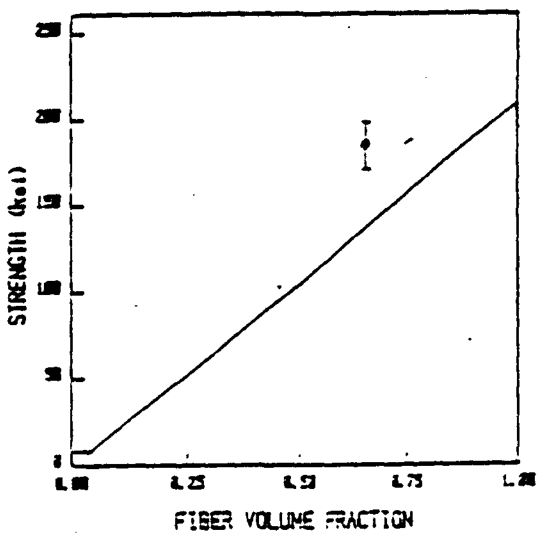


THEORETICAL MODULUS PREDICTION
FOR AS4-3K GRAPHITE/EPOXY COMPOSITE

(4) Tensile Strength

Ko's model generates a conservative prediction for the tensile strengths of MAGNAWEAVE composites, as the figure below demonstrates.

Figure XI



THEORETICAL STRENGTH PREDICTION
FOR AS4-3K GRAPHITE/EPOXY COMPOSITE

These models are available, and will be used to define the weave geometry required for the shapes fabricated with the turbine braider.

D. Effect of Varying Fiber Count and Fiber Volume

A number of cases were studied in which fiber volume and fiber count were varied to determine their effect on machine design parameters. Specifically, the four cases below were studied:

Case	Fiber Volume	Fiber Count
I	0.25	500
II	0.25	2000
III	0.40	2000
IV	0.25	1265

Case IV shows the fiber count required if the machine parameters of Case III were applied to fiber volume of 0.25

The results are summarized in Table VII below. From the data presented the following relations emerge:

1. Of prime significance, for a single set of machine parameters, the fiber volume can be controlled by varying only the filament count. Therefore, the machine parameters selected for Phase II will produce turbine rotors of a range of fiber volumes.
2. For a given fiber volume, increasing the fiber count decreases the number of rings and the numbers of elements/ring required.

TABLE VII

Summary of Parametric Study

Characteristics	Case I	Case II	Case III	Case IV
1.Fiber Volume	0.25	0.4	0.25	0.25
2.Fiber Count	1200	2000	2000	500 filament
3.Design Diameter	4.025	4.025"	4.025	4.025"
4.Design Circ.	12.65"	12.65"	12.65"	12.65"
5.Effective Fiber Area	6.25×10^{-4}	4.9×10^{-4}	19.6×10^{-4}	4.9×10^{-4}
6.Unit Cell Size	0.025	0.035"	4.4×10^{-2}	2.2×10^{-2}
7.Elements/Ring	360	360	288	575
8.Spokes/Blade	16	16	8	16
9.Spoke Length/ Element	0.105	0.105	0.132	0.066
10.Rings (mobile)	18	18	15	30
11.Rings (total)	24	24	21	36

Case III was selected for further evaluation. The combination of maximum filament size and maximum fiber volume permits a reduction in the number of rings required while maximizing the mechanical properties attainable for the preform.

V. Representative Machine Loading and Motion Sequences

In the course of the analysis, successive exercises were conducted to assess design decisions and further the understanding of machine motion requirements. In developing the final design concept, a succession of shapes of increasing complexity were used for the generation of machine loading and motion sequences:

A. Thick-walled disc

B. 36-finned disc

C. 36-finned disc with progressive insertion

D. 36-bladed rotor with thin blades

The loading patterns and motion sequences for each of these examples appears below.

A. Thick-Walled Disc

The initial configuration considered was a thick walled disc, whose inner diameter would accommodate a hub and whose loading would cover an ID to OD radius of about three inches.

For this exercise, the total number of rings was taken as 30, in this sequence:

1. Rings 1, 2, 3, stationary
2. Rings 4 through 27, mobile
3. Rings 28 through 30, stationary

1. <u>Machine Loading</u>

The loading pattern was an attempt to achieve minimal changes in fiber volume with increasing radius by separating the rings into three bands, each band loaded differently and each band moving differently.

a. Rings 1, 2, 3 loaded in spoke 10, 28, 46 . . .

b. Rings 4, 5, 6 loaded 1, 10, 19, 28, 37, 46 . . .

c. Rings 7, 8, 9 loaded 1, 4, 10, 16, 19, 22, 28 . . .

d. Rings 10 through 16 loaded 1, 4, 7, 10, 13, 16, 19, 22 . . .

e. Rings 17 through 19 loaded 1, 2, 4, 6, 7, 8, 10, 12, 13, 14 . . .

f. Rings 20 through 27 filled

g. Rings 28 through 30 loaded 1, 3, 5, 7, 9 . . .

2. <u>Machine Motion</u>

The machine motion sequence follows the pattern shown on the following page.

This motion sequence permits the ring motion to occur when no elements are present in those rings as a consequence of their being used as "rest rings" for the denser bands.

3. Loom Motion Sequence

1. Rings 27, 25, 23, and 21 move one spoke clockwise
   Rings 20, 24, 22, and 20 move one spoke counterclockwise

2. Spokes 2, 6, 8, 12, 14, 18, 20, 24, 26, 30, 32, 36, 38, 42, 44, 48, 50, 54, 56, 60 cross three rings outward

3. Rings 19, 17, 15, 13, and 11 move three spokes clockwise
   Rings 18, 16, 14, 12, and 10 move three spokes counterclockwise

4. Spokes 4, 16, 22, 34, 40 cross three rings outward

5. Rings 9, 7, 5 move nine spokes clockwise
   Rings 8, 6, 4 move nine spokes counterclockwise

6. Spokes 10, 28, 46 cross three rings outward

7. Spokes 1, 3, 5, 7, 9, 11, 13, 15, 17, 19, 21, 23, 25, 27, 29, 31 33, 35, 37, 39, 41, 43, 45, 47, 49 move three rings inward

8. Rings 27, 25, 23, and 21 move one spoke counterclockwise
   Rings 26, 24, 22, and 20 move one spoke clockwise

9. Spokes 3, 5, 9, 11, 15, 17, 21, 23, 27, 29, 33, 35, 39, 41, 45, 47 cross three outward

10. Rings 19, 17, 15, 13, and 11 move three spokes counterclockwise
    Rings 18, 16, 14, 12, and 10 move three spokes clockwise

11. Spokes 7, 13, 25, 31, 43, 49 cross three rings outward

12. Rings 9, 7, 5 move nine spokes counterclockwise
    Rings 8, 6, 4 move nine spokes clockwise

13. Spokes 19, 37 cross three rings outward

14. Spokes 2, 4, 6, 8, 10, 12, 14, 16, 18, 20, 22, 24, 26, 28, 30, 32, 34, 36, 38, 40, 42, 44, 46, 48, 50 cross three rings inward

Repeat sequence for steps 1 through 14.

Figures XII - XIX follow these motion sequences, with each figure showing the motion for various elements through the machine for each sequence.

Figure XII

Motion I for Thick Walled Disc

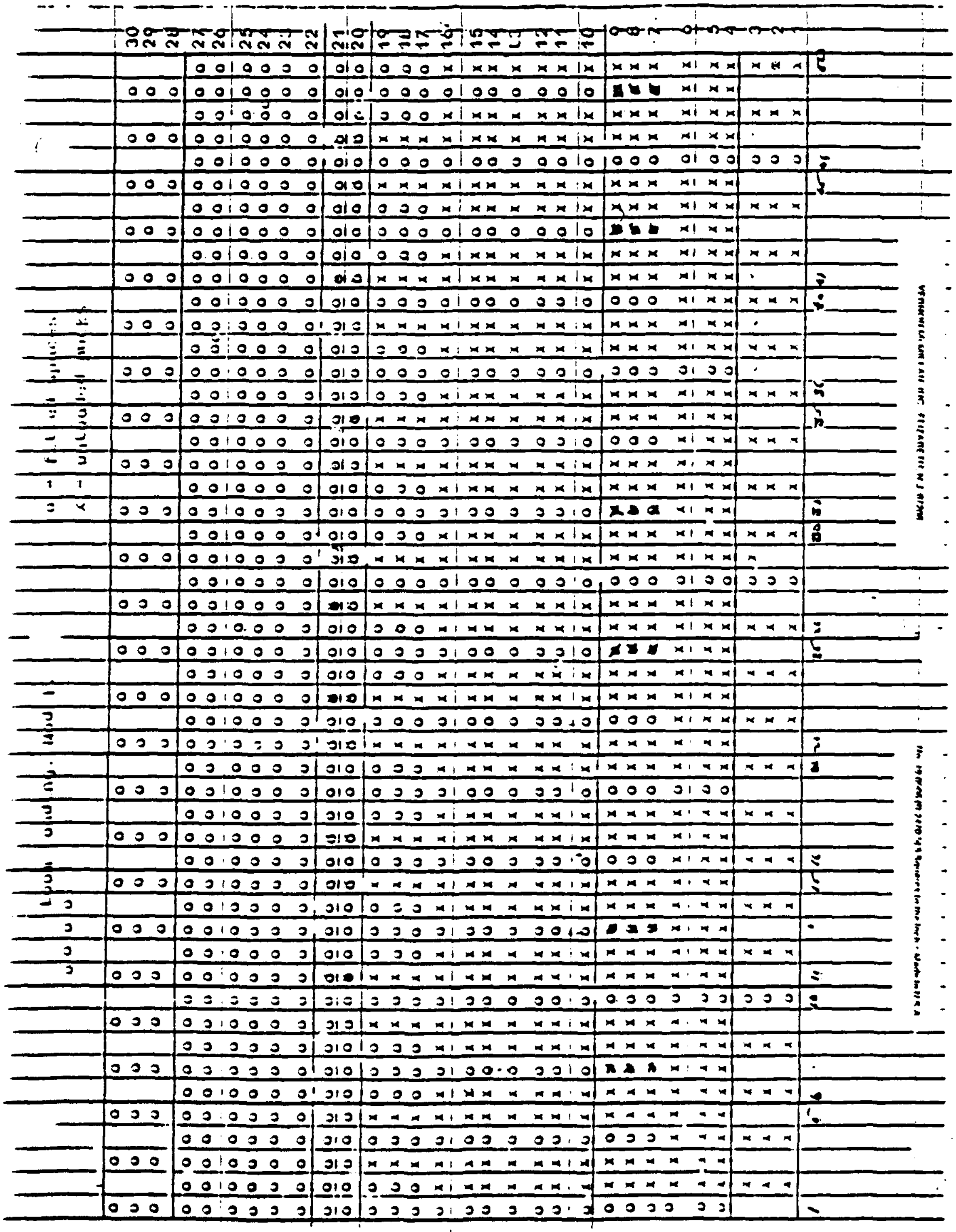


Figure XIII

Motion II for Thick Walled Disc

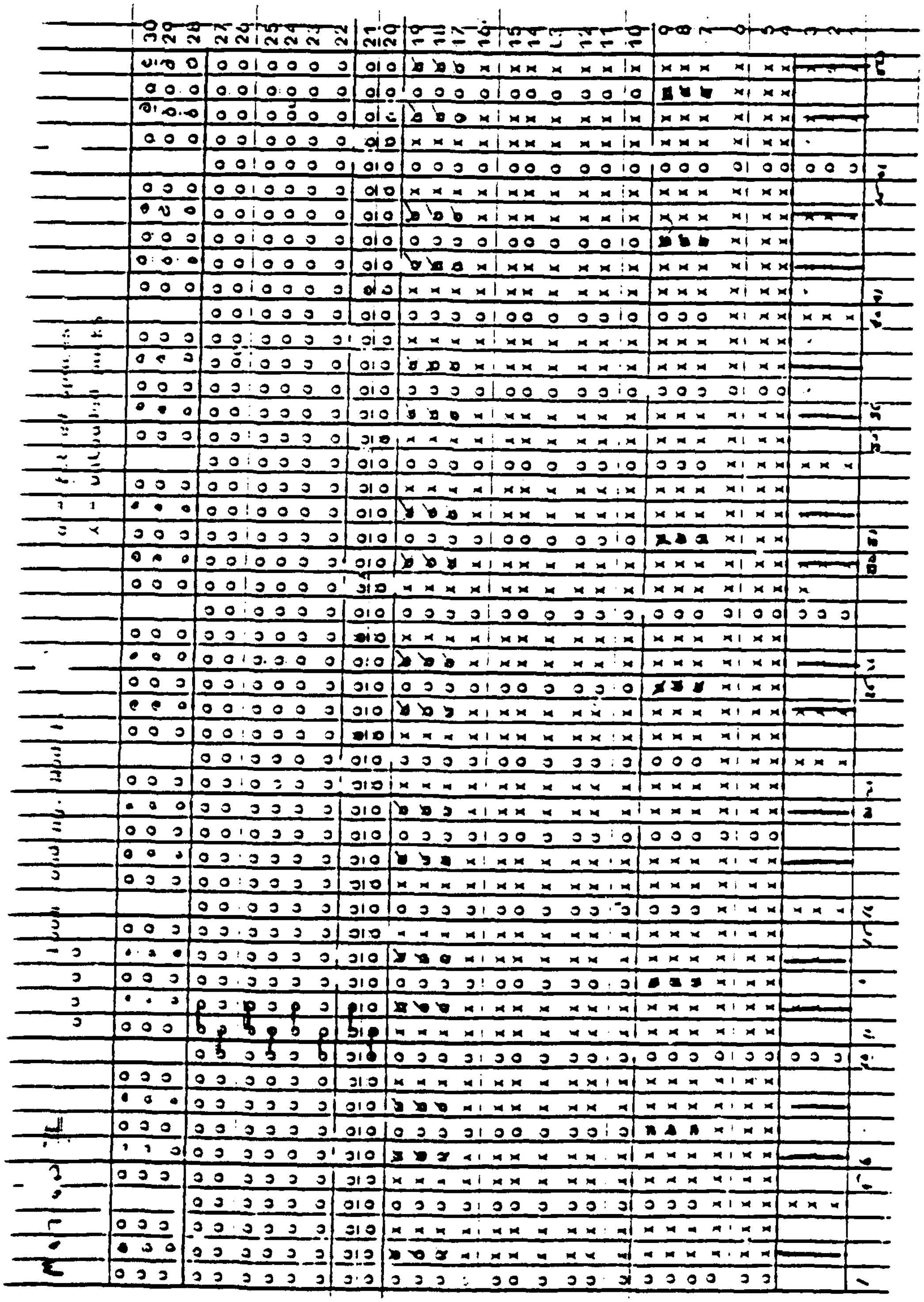


Figure XIV

Motion III for Thick Walled Disc

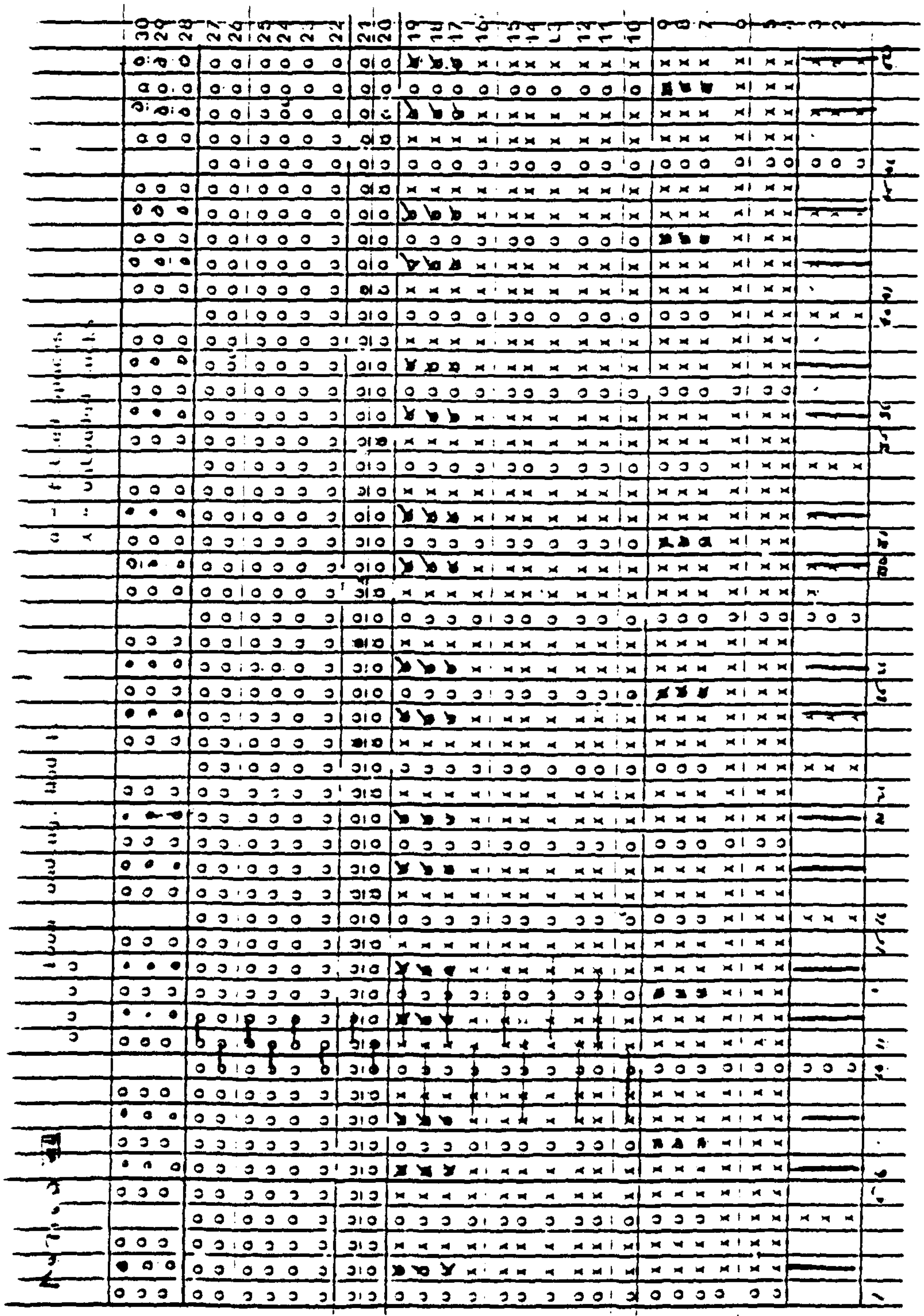


Figure XV

Motion IV for Thick Walled Disc

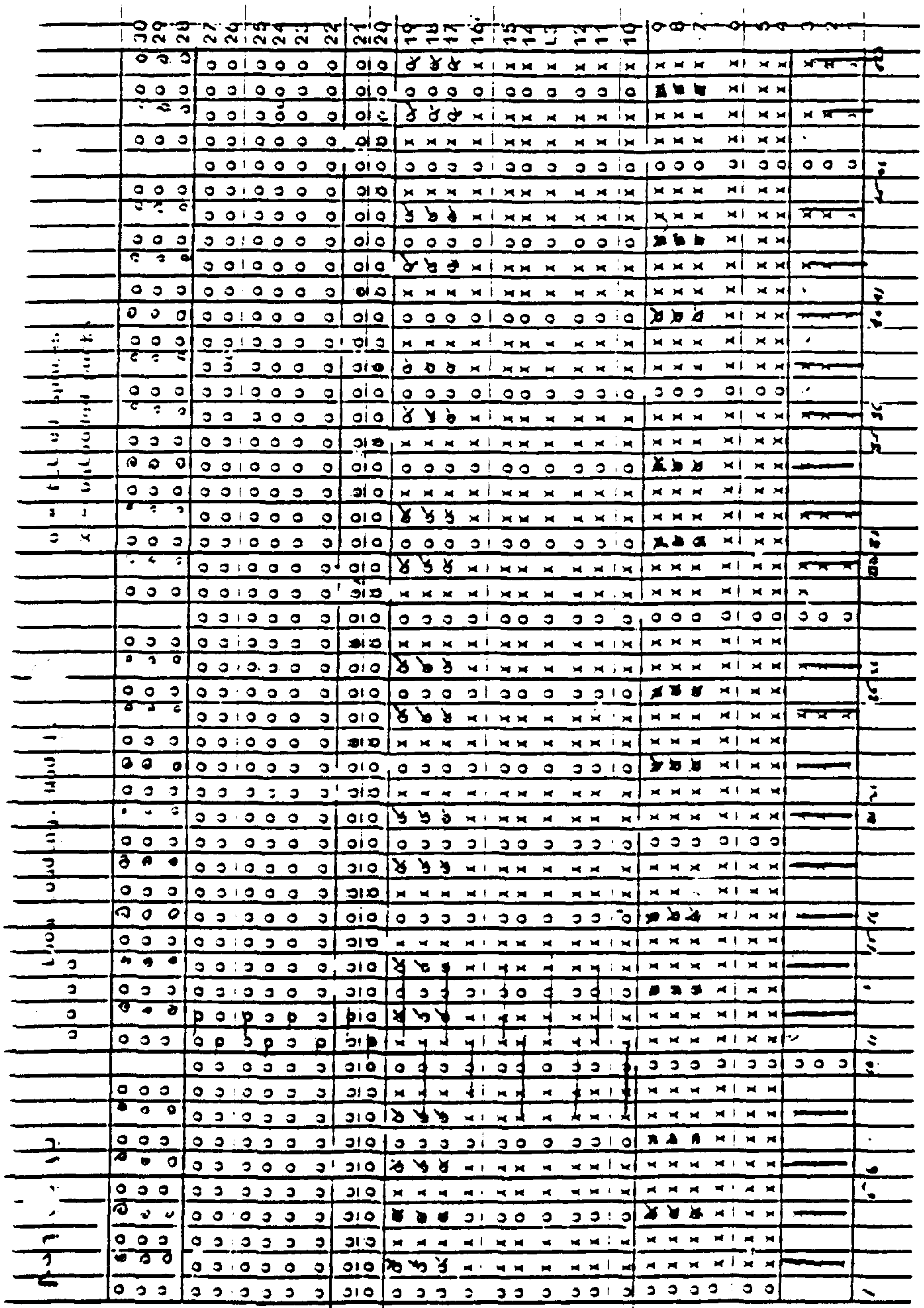


Figure XVI

Motion V for Thick Walled Disc

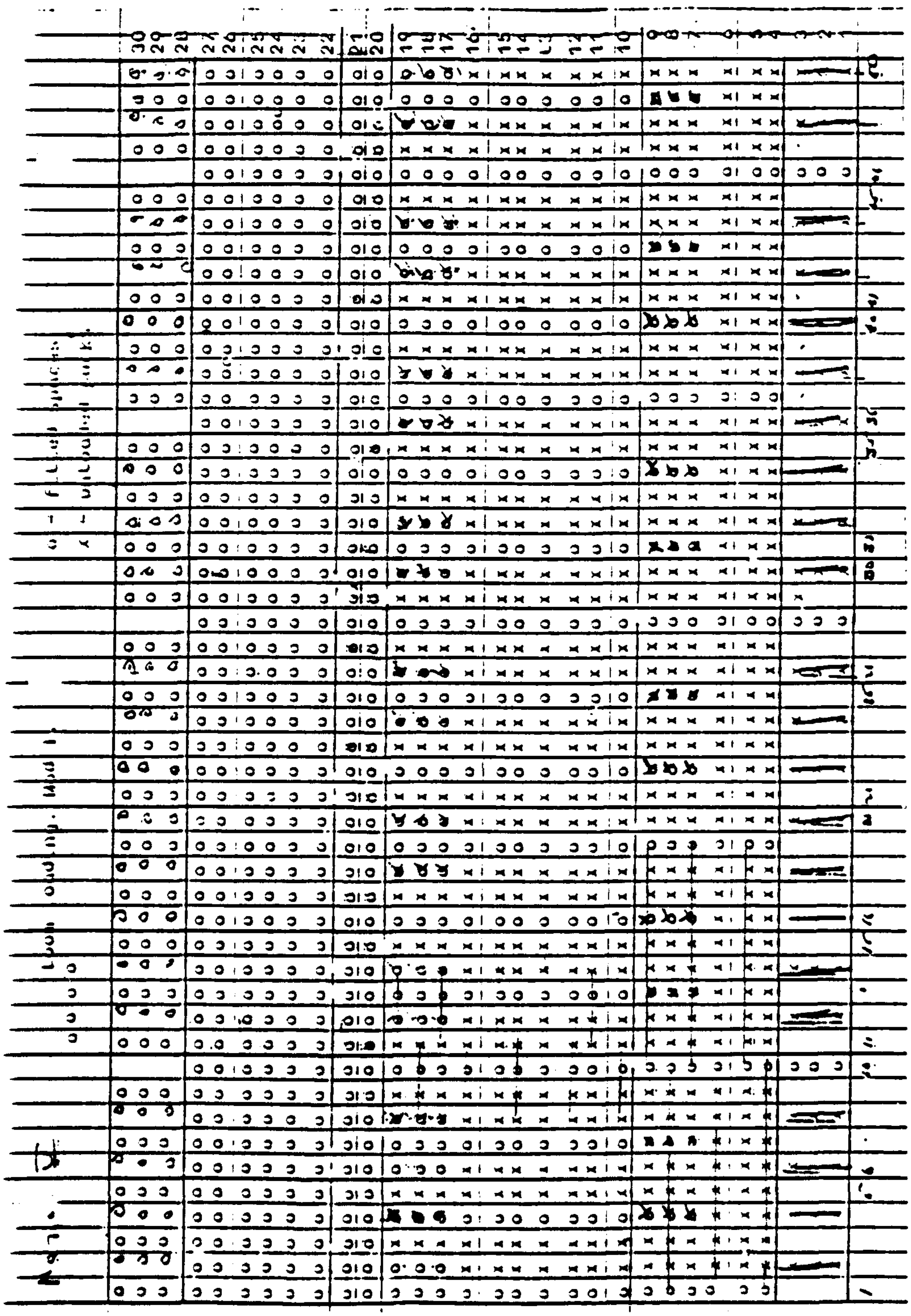


Figure XVII

Motion VI for Thick Walled Disc

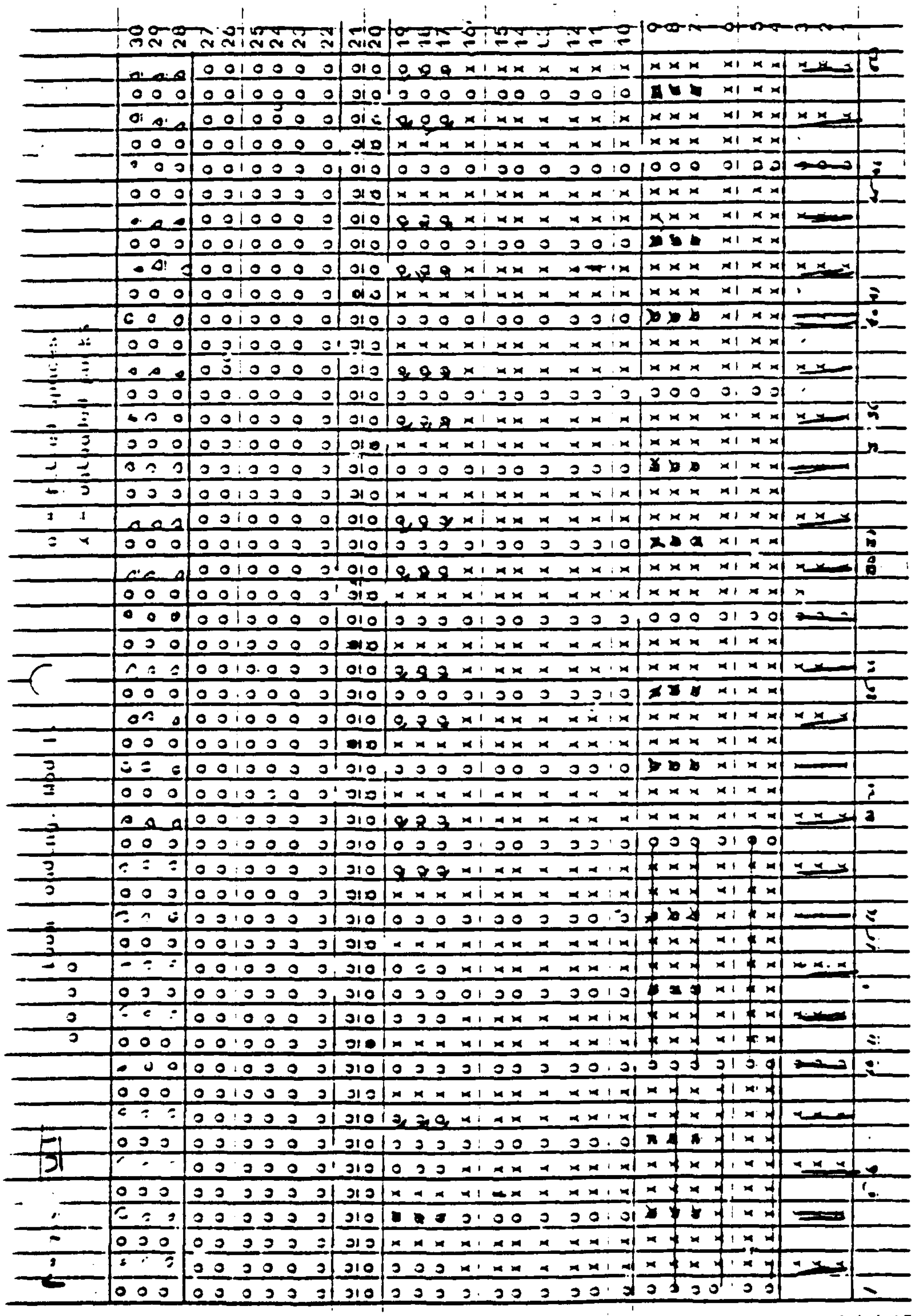


Figure XVIII

Motion VII for Thick Walled Disc

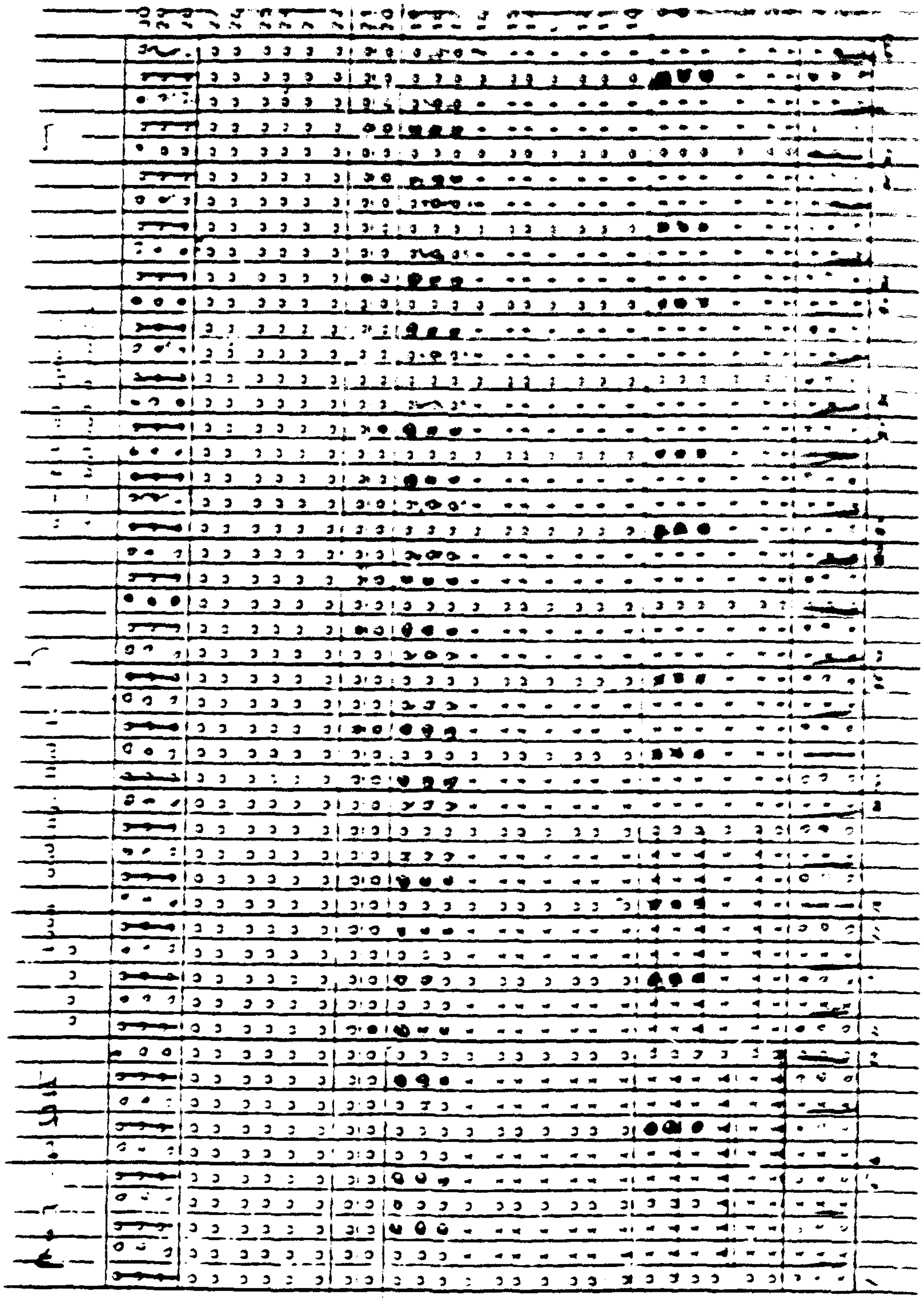
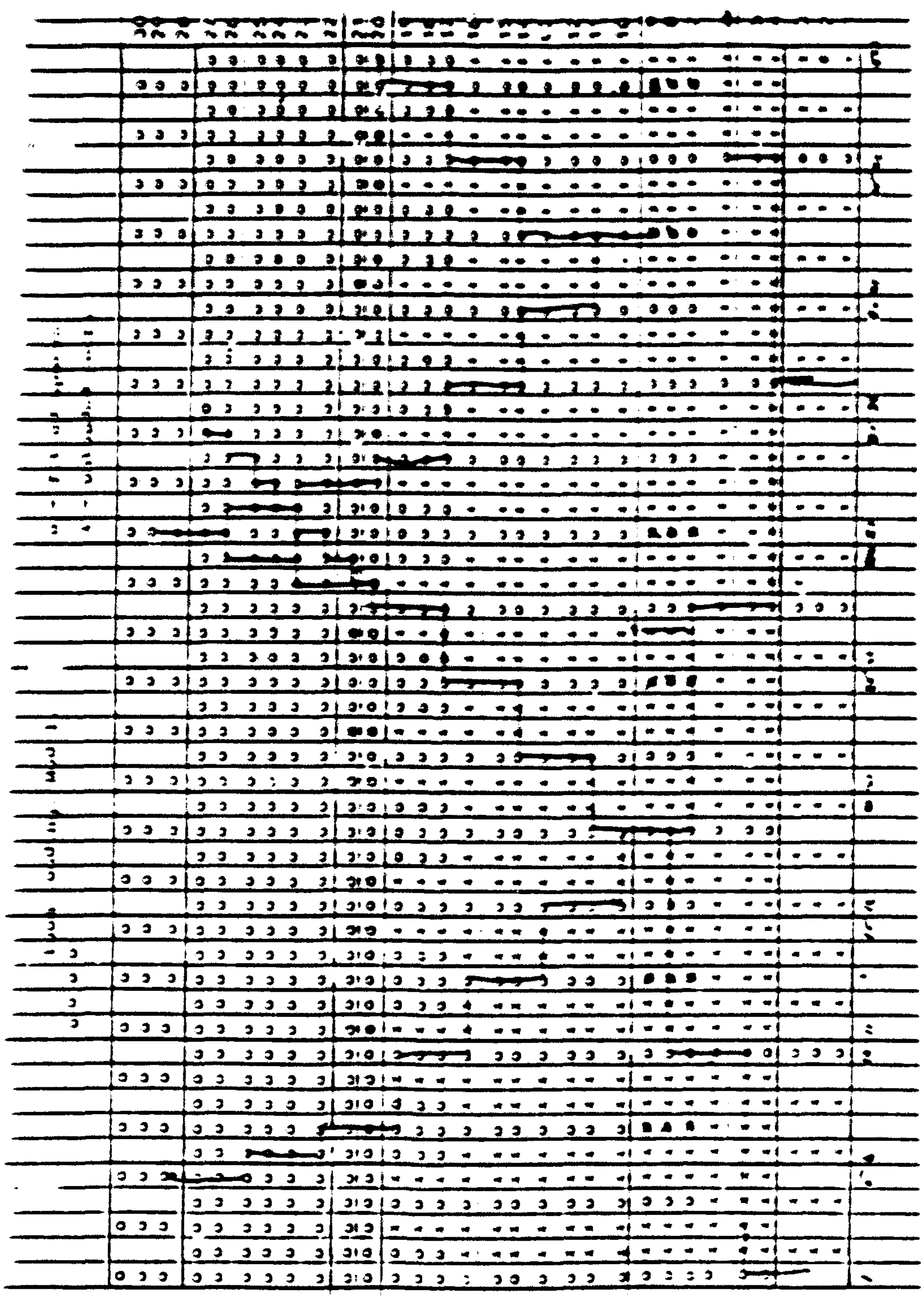


Figure XIX

Element Movement in Thick Walled Disc



B. 36-Finned Disc

The next shape toward the configuration of interest was a finned disc, where fins are defined as blades with a constant cross section from inner edge (adjoining the disc) to outer limit. This configuration is forerunner of the 36-bladed turbine wheel.

The Williams' dimensions were used, which reduced the total of rings to 24, with the three innermost and three outermost rings stationary, and 18 mobile rings in between.

1. Assumptions

The width of the fin is accounted for by 4 active and 2 passive spokes.

The length of the fin is accounted for by 6 active and 3 inactive rings (mobile and stationary)

Weave geometry is as for the cylinder; 1 x 3 x 1

2. Machine Loading

Machine loading was accomplished in a manner similar to that for the thick walled cylinder, with separate segments in the six mobile outer ring accounting for the fins.

3. Ring Motion

Rings 24, 23, and 22 are stationary
Rings 21, 19, and 17 move one spoke together
Rings 20, 18, and 16 move one spoke together, in opposition to rings 21, 19, and 17
Rings 15, 13, 11, and 9 move three spokes
Rings 14, 12, 10, and 8 move three spokes
Ring 7 and 5 move nine spokes
Rings 6 and 4 move nine spokes
Rings 1, 2, and 3 are stationary

See Figure XXI.

Figure XX

Machine Loading for 36-Finned Disc

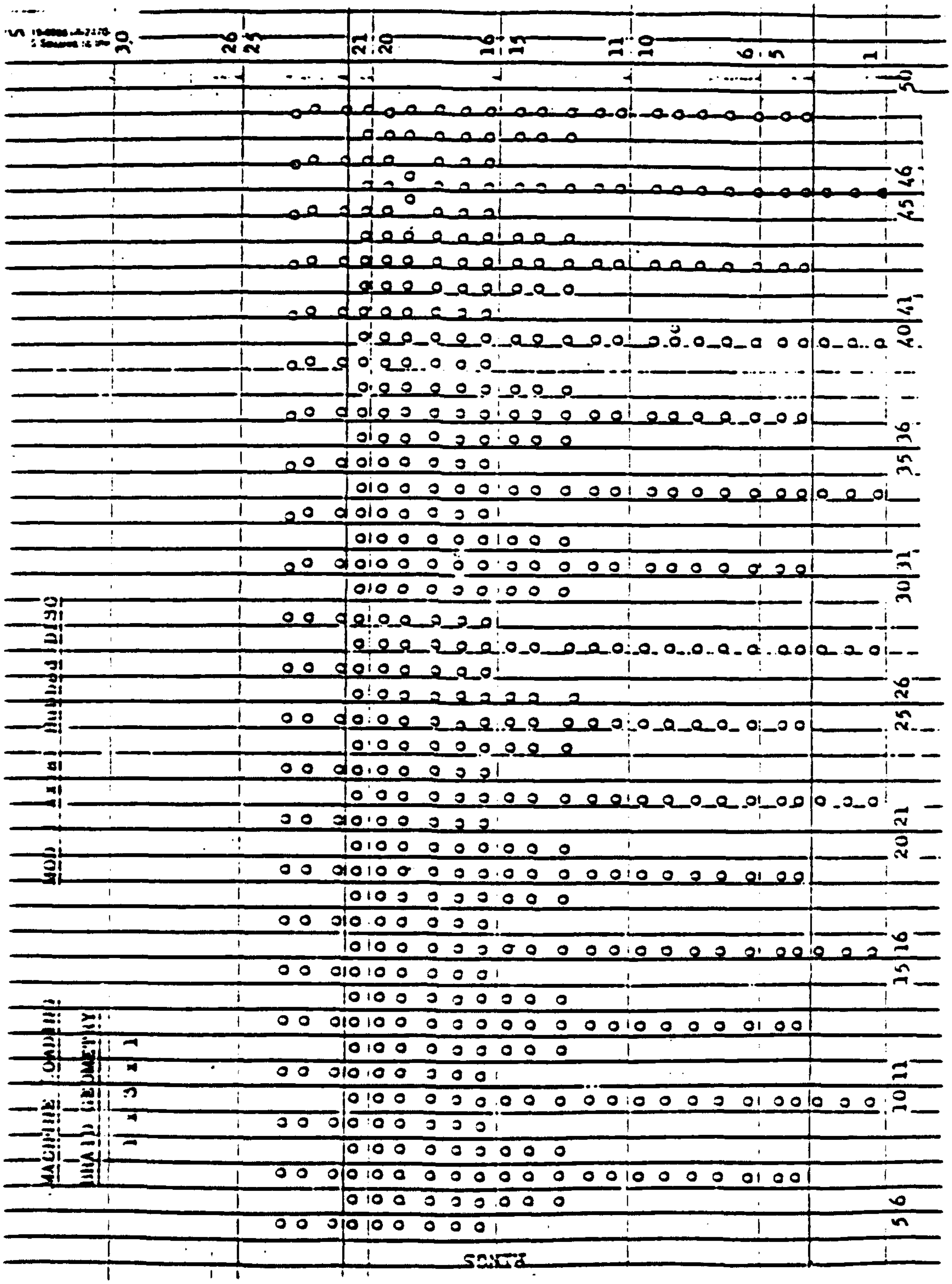
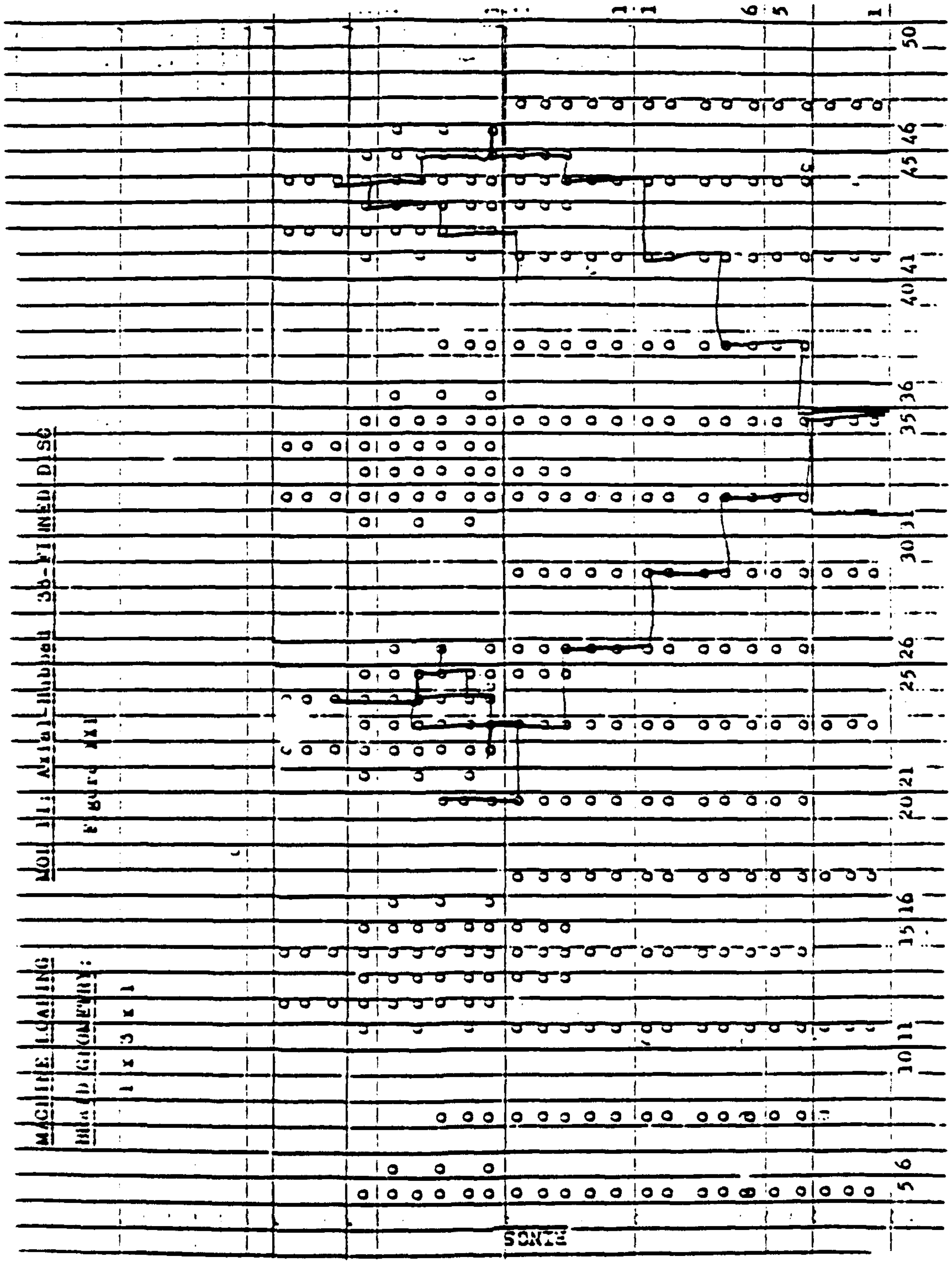


Figure XXI

Machine Loading for 36-Finned Disc



C. 36-Finned Disc, Progressive Insertion

The underlying rationale for this exercise was to try to maintain constant fiber volume as additional rings were added by varying the loading of the machine. The basic concept is derived from the prior exercise. In this case, for each subsequent ring, as the radius increases, enough additional fibers, spaced around the circumference, are added to maintain constant fiber volume. These additional fibers are included in the braid structure, although they do not participate in the braiding themselves. The direction of the fibers is dictated by the braid structure formed. In this case the fibers will move radially and make a major contribution to the required radial strength of the parts.

Therefore, by this technique of progressively inserting additional fibers, a preform with constant fiber volume and additional fibers in prescribed directions can be achieved.

The machine loading is defined below, and is shown in Figure XXII. The machine motion is identical to the prior exercise.

1. Machine Loading for Basic Braid

   a. Rings 1, 2, 3 load spokes 1, 7, 13, 19 . . .
   b. Rings 4 through 13 load 1, 4, 7, 10, 13, 16, 19, 22 . .
   c. Rings 14 through 15 load all spokes
   d. Load rings 16 to 24 for fins.

2. Machine Loading for Added Fibers

See Table 8 below, Figure XXII shows the insertion of added fiber.

TABLE VIII

Ring Loading for Constant Fiber Volume

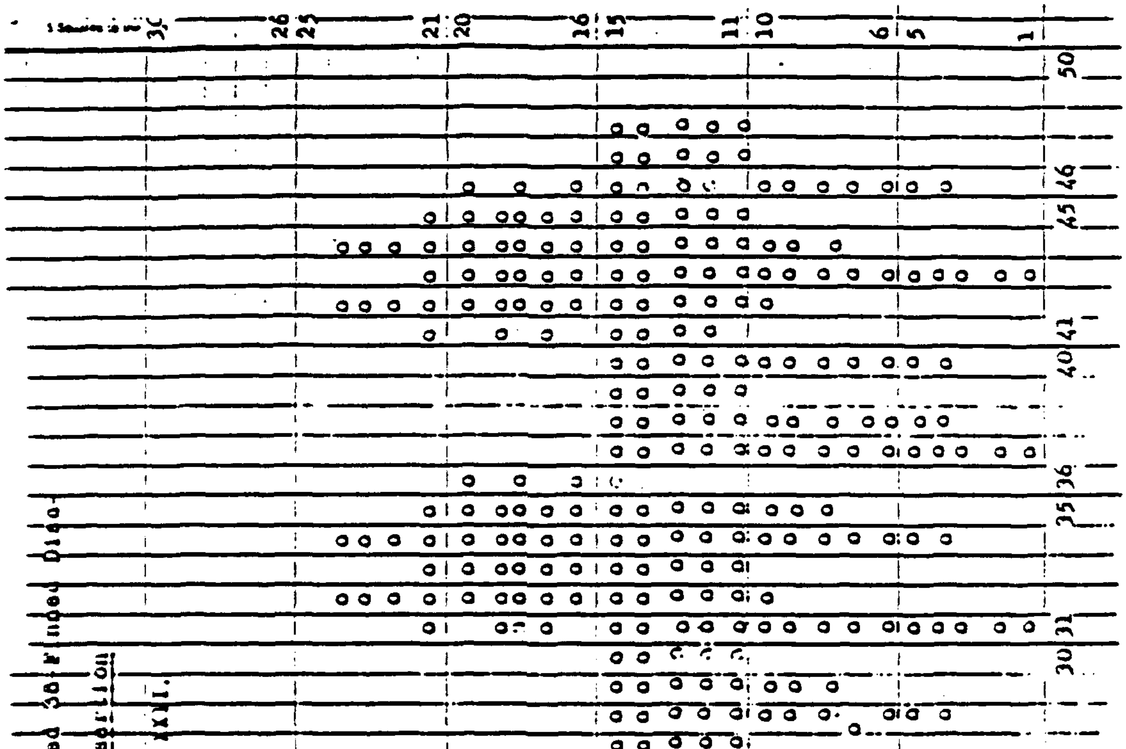
Ring	Radius	N_r
1 (fixed)		60
2 (fixed)		60
3 (fixed)		60
4	0.665	120
5	0.770	140
6	0.875	160
7	0.980	180
8	1.085	200
9	1.190	220
10	1.295	240
11	1.400	260
12	1.505	280
13	1.610	300
14	1.715	320
15	1.820	340

Rings 16 through 24 are used to form the fins.

Figure XXII

Machine Loading for Axial Hubbed

36-Finned with Progressive Insertion



D. 36-Bladed Rotor, Thin Blades

A natural extension to the 36-finned disc is the 36-bladed rotor. The blades are identical in number to the fins, but their dimensions and shape are complex. Their most prominent feature is the narrow width of the blade.

The earlier exercises assumed a tow size of 0.04" in diameter; this results in a fin with a minimum width of 0.08". To make a narrower blade would require a smaller tow size. A diameter of 0.02" (500 versus 2000 filaments) would result in a blade with a minimum width of 0.04".

To achieve thin bladed rotors without increasing machine size (additional rings) we resort, therefore, to a practice developed some time ago of using two different tow sizes in the braid fabrication. This requires additional machine complexity -- an additional set of moving rings -- so that the regions occupied by each tow size be separated from, although intertwined with, each other.

Therefore, altering the machine design may permit the fabrication of complex, thin rotor blades by using multiple tow sizes.

Figure XXIII describes a loading using two separate fiber sizes. The numbered elements are occupied by thin filaments, the lettered elements are occupied by thick filaments. The example shown is demonstrative of the loading required for this example.

Figure XXIV shows the paths followed by a representative thin fiber and thick fiber in the example used in Figure XXIII.

Figure XXV shows the actual loading for a thin-bladed turbine rotor as described above. The ring motions are identical with the exception of the two rings which make the interface between the blades and the body of the rotor (Figure XXVI). The patterns for these two rings follow the example in Figure XXIV.

Machine Loading

The machine is loaded, following Figure XXV. In order to braid blades with decreased thickness (requiring thinner fibers, additional mobile rings will be required, as shown in the figure.

Rings 16 through 30 are loaded with fibers with 500 filaments/fiber. Loading is in discrete segments around the rings, with each segment braiding a single blade, integral with the body.

Rings 1 through 15 are loaded as in the figure. This loading duplicates the loading for the 36-bladed rotor shown in Figure XXIII.

Ring Motion Sequence

Rings 30, 29, and 28 are stationary.

Rings 27, 25, 23, 21, 19, and 17 move in the same direction, one spoke.

Rings 26, 24, 22, 20, and 18 move in the opposite direction, one spoke.

Ring 16 moves two spokes, together, in direction, with rings 26, 24, etc.

Ring 15 moves two spokes in the direction opposite to ring 16.

Rings 14, 12, 10, 8, 6, and 4 move three spokes in the same direction as rings 26, 24, etc.

Rings 13, 11, 9, 7, and 5 move three spokes in the direction opposite to rings 4, 6, 8, etc.

Spoke motion will be shown in the machine motion sequence below.

Machine Motion Sequence

1. Move rings 4, 6, 8, 27, 25, 23, 21, 19, and 17 one spoke clockwise.
2. Move rings 26, 24, 22, 20, and 18 one spoke counterclockwise.
3. Move ring 16 two spokes counterclockwise.
4. Move spokes 24, 26, 28, 30, etc. three rings outward.
5. Move ring 15 two spokes counterclockwise.
6. Move rings 14, 12, 10, 8, 6, and 4 three spokes clockwise.
7. Move rings 13, 11, 9, 7, and 5 three spokes counterclockwise.
8. Move rings 8, 25, 27, 29, 31, etc, three rings inward

Repeat motion sequence.

Figure XXIII

Loom Loading for Bi-Layer Interbraid

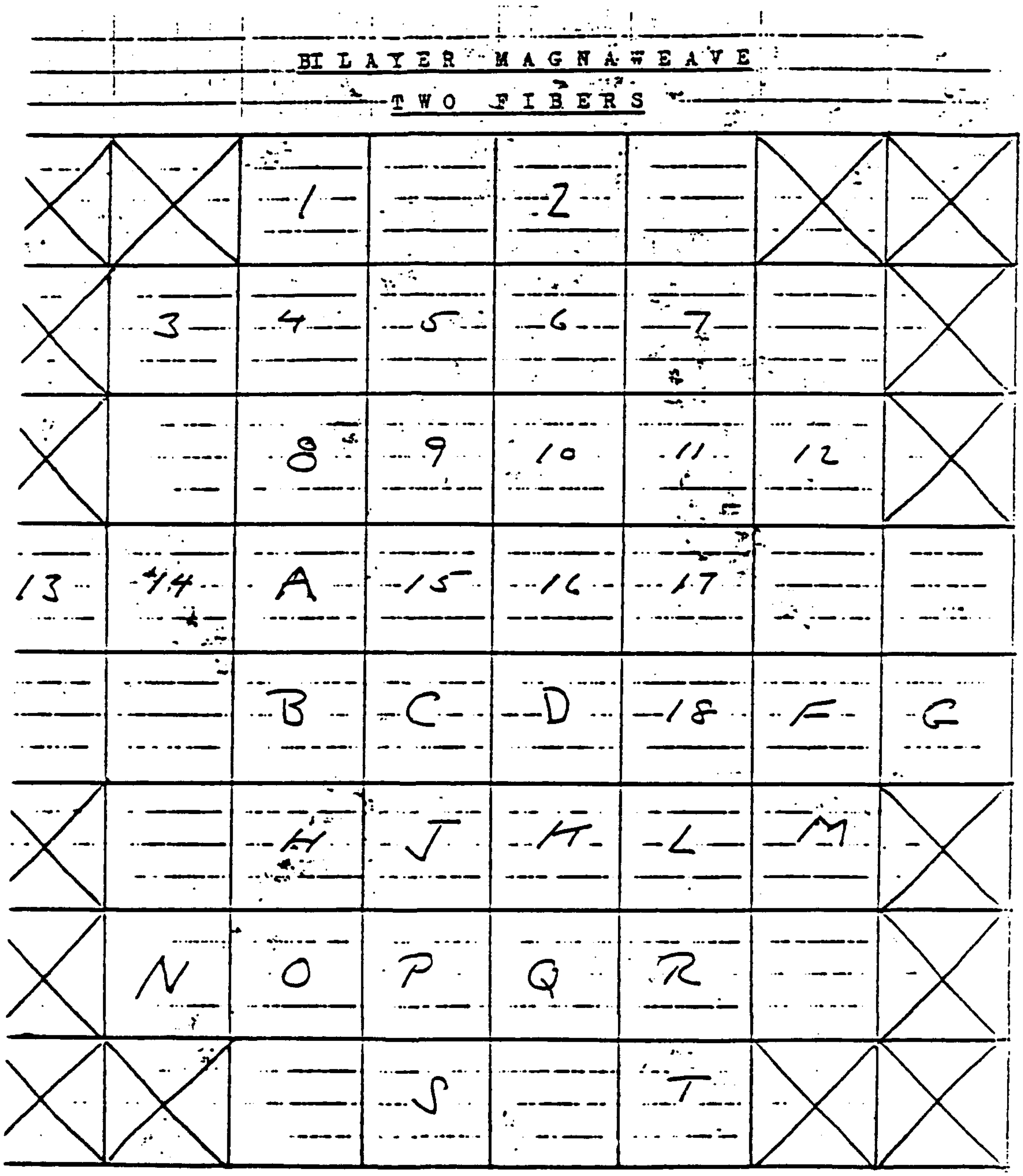


Figure XXIV

Fiber Motion for Bi-Layer Interbraid

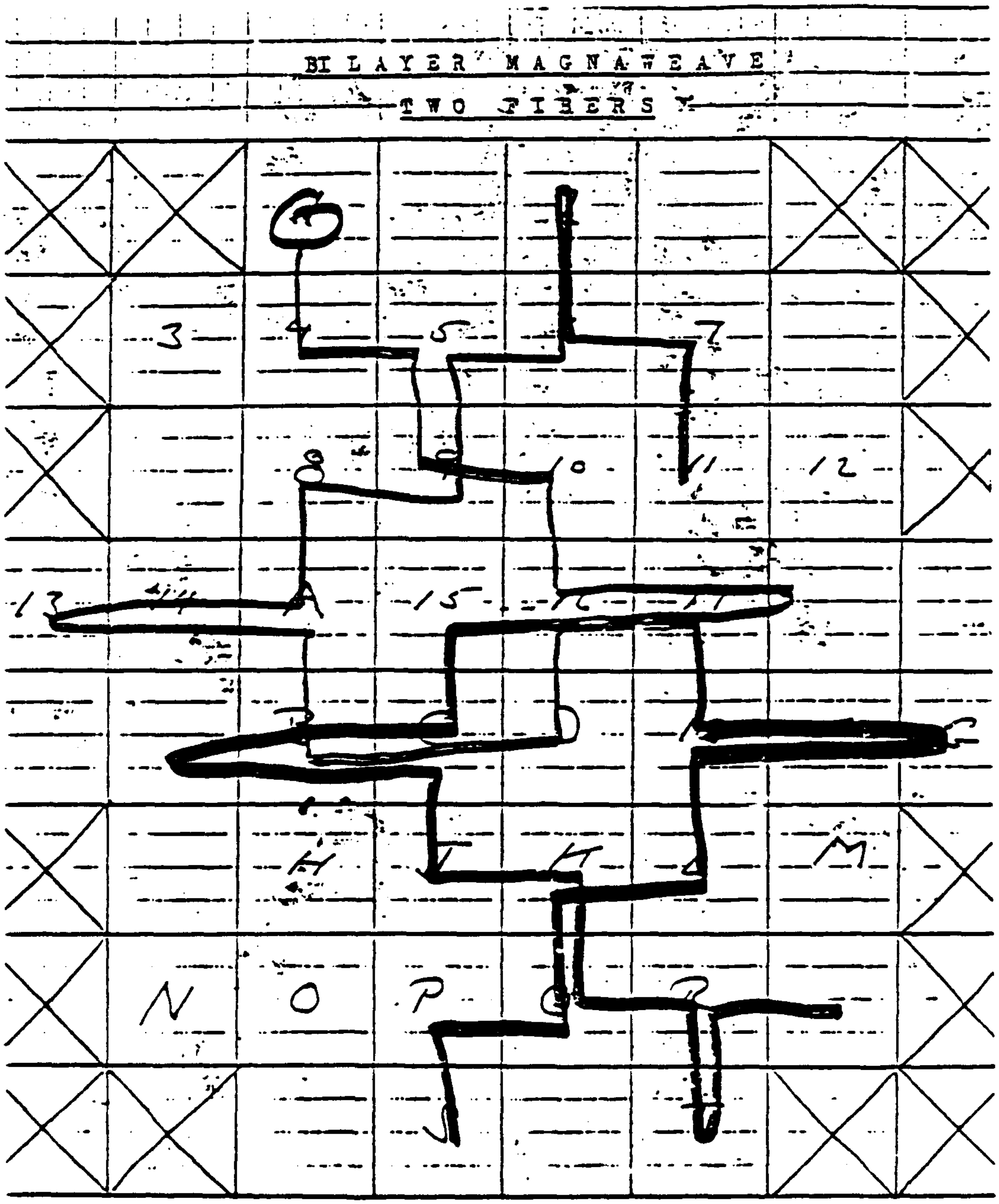


Figure XXV

Machine Loading for 36-Bladed Rotor

with Air Foil Blades

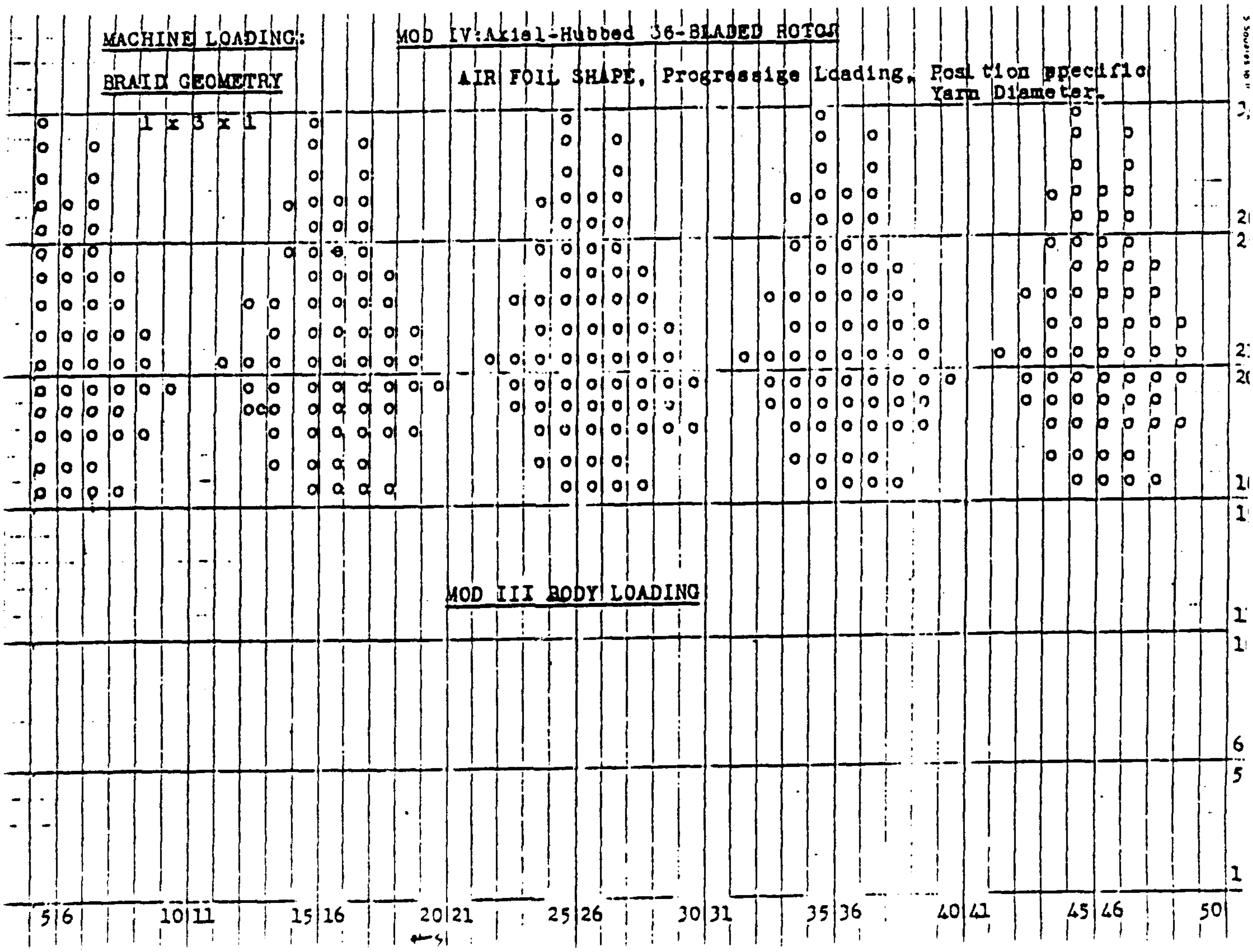
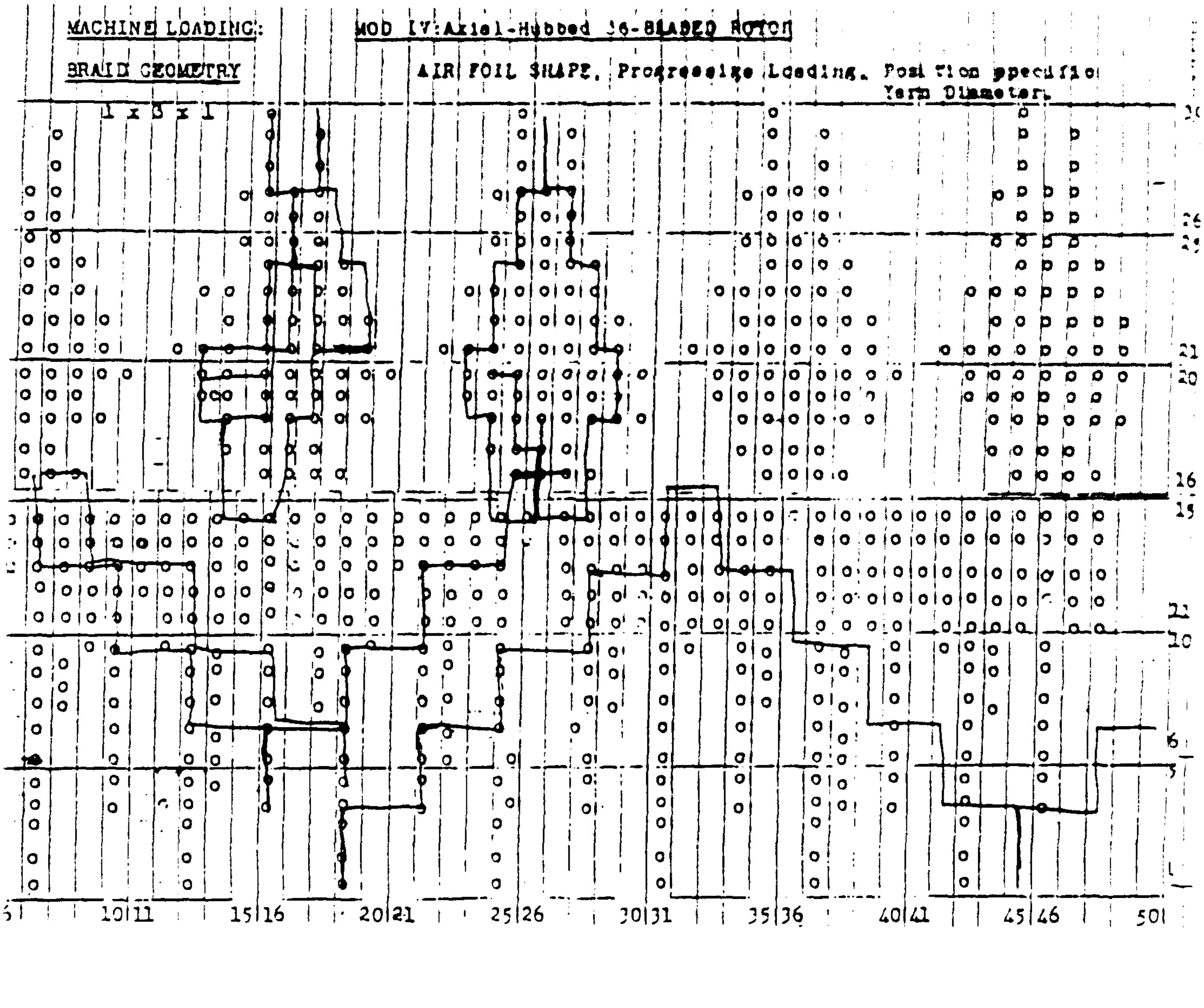


Figure XXVI

Machine Loading for 36-Bladed Rotor

with Air Foil Blades



VI. MAGNASWIRL Machine Design for Turbine Rotor Preforms

A. Objective

Build a three dimensional braiding machine that can produce a generic turbine rotor preform from silicon carbon fibers. Prove out weave patterns, yarn loading, machine operation, preform shape and fiber materials. Supply preforms for matrix induction.

B. Part Specification

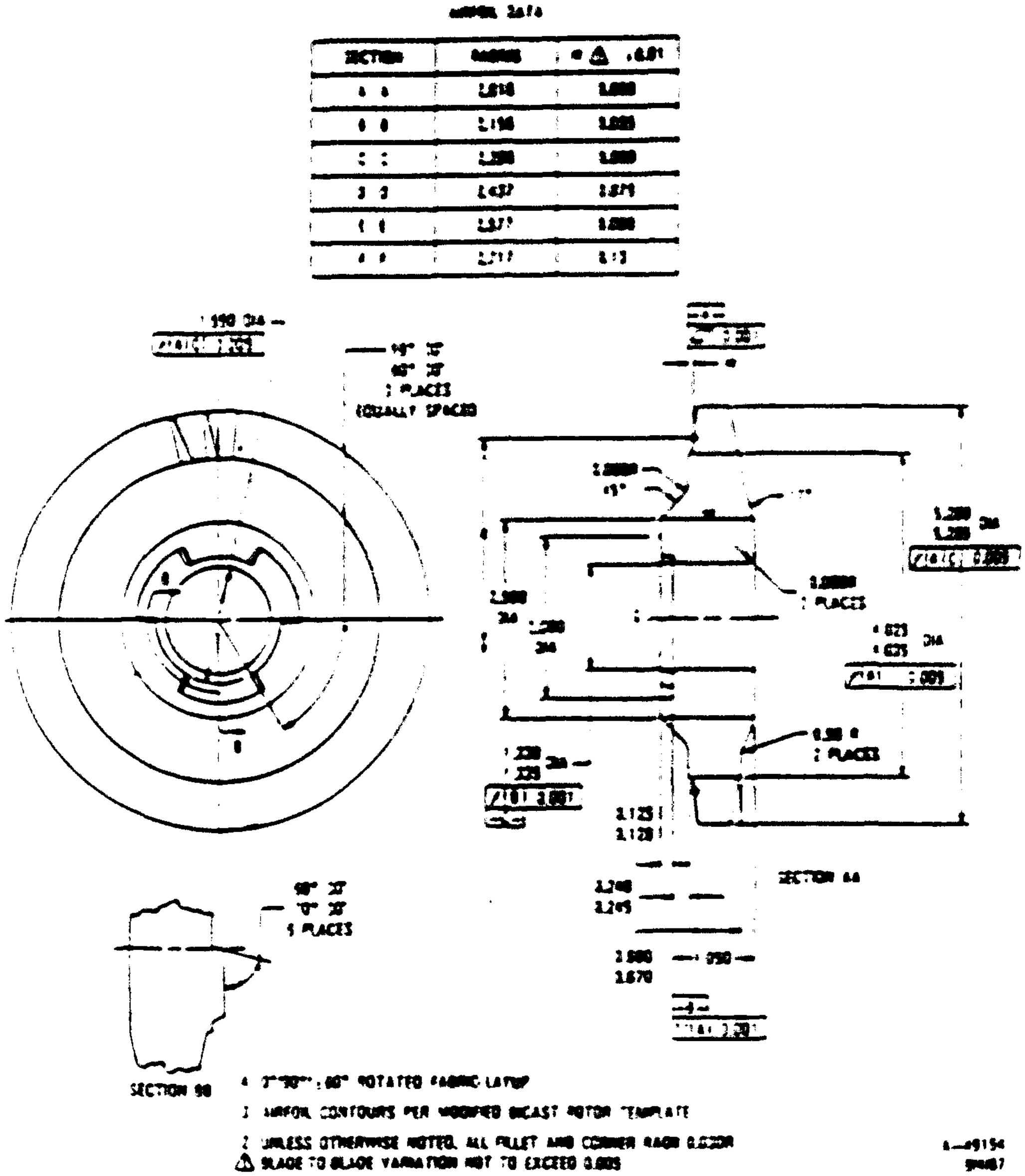
Figure VIII shows a drawing of a typical rotor with a series of 32 to 45 blades on the circumference. The machine will be designed to braid a preform of a generic rotor shape with integrally braided blades as shown in Figure XXVI. Specified are 36 blades as a typical number in the specified range.

Since the turbine rotor represents a high strength, high temperature application, the preform is to be braided with silicon carbide fibers.

C. Machine Specifications

Based on a yarn density of 8 yarns per inch the number of elements required for the machine can be calculated.

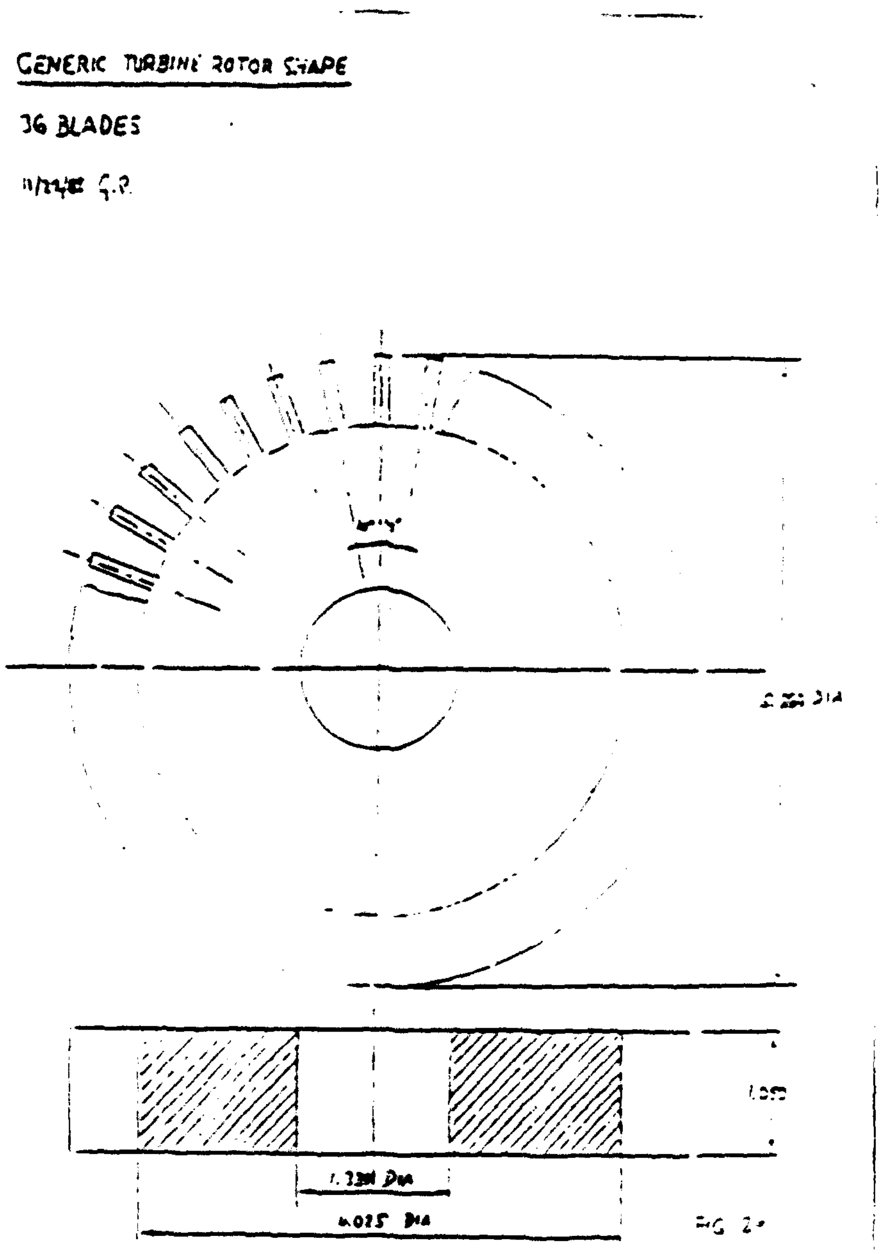
Figure VIII



WR24-7 Ceramic Composite Rotor Design Drawing.

Figure XXVII

Generic Turbine Rotor Shape



1. Radial Direction

A total of 24 moving rings is required plus three stationary rings on the inside and outside of the moving rings. Numbering the rings from the inside to the outside, the ring motion requirements are as follows:

1.1 Rings 1 through 3: stationary.

1.2 Rings 4 through 21: rings move 3 positions at a time, alternate rings moving in opposite direction. This action forms the hub.

1.3 Rings 22 through 27: rings move 1 position at a time, alternate rings moving in opposite direction. This section forms the blade.

1.4 Rings 28 through 30: stationary.

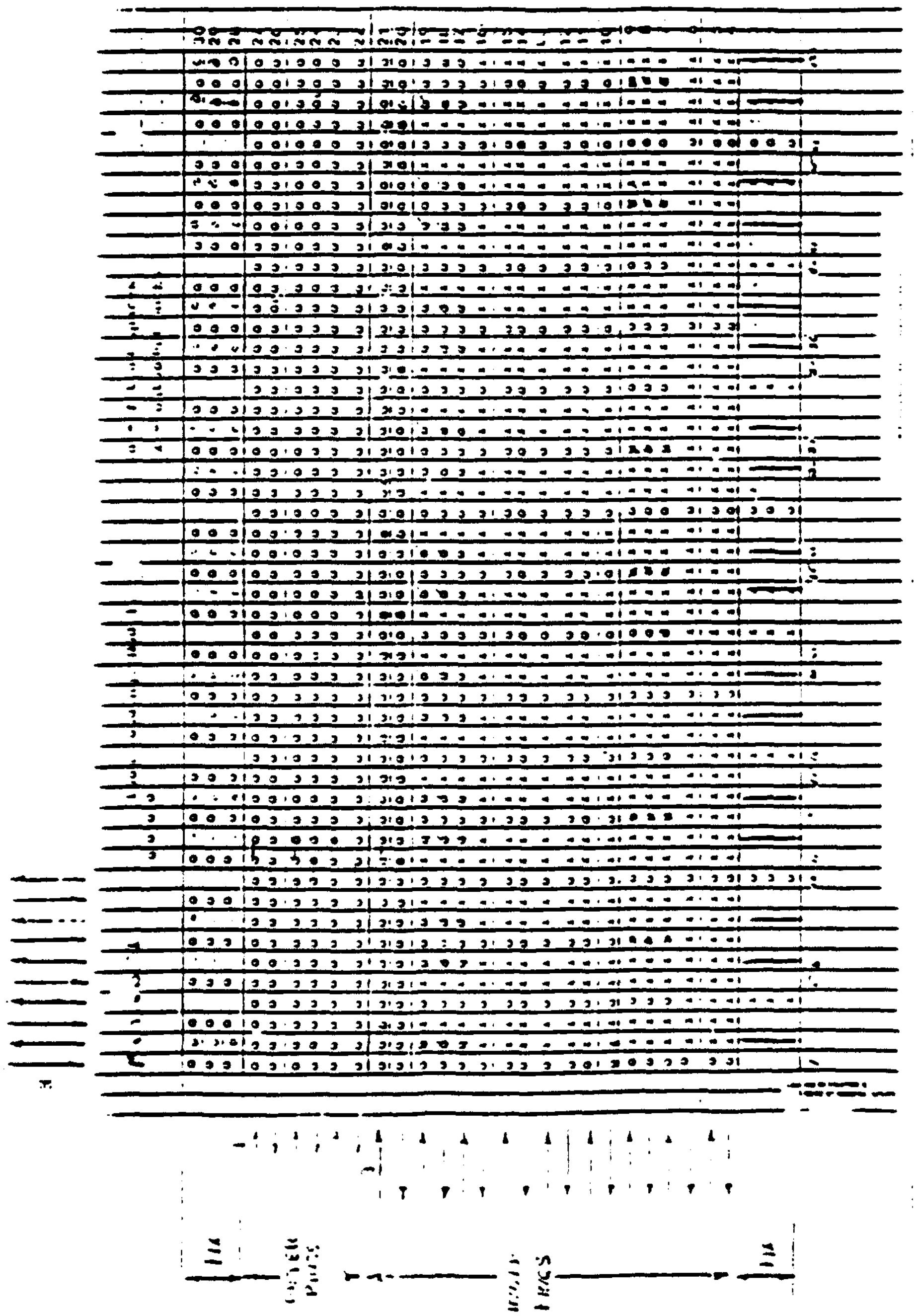
A schematic of the ring motions is shown in Figure XXVIII

2. Circumferential Direction

A total of 360 yarn carrying elements are required on each of the rings, which means that the yarn carriers travel in 360 radial

Figure XXVIII

Circular Loom Motions



slots through the rings.

2.1 All elements travel in radial direction 3 steps at a time, alternate "spokes" moving in opposite direction.

3. <u>Total Number of Elements</u>

3.1 For this specified array of 24 moving rings and 360 elements on the circumference of each ring the total number of elements required is 9720.

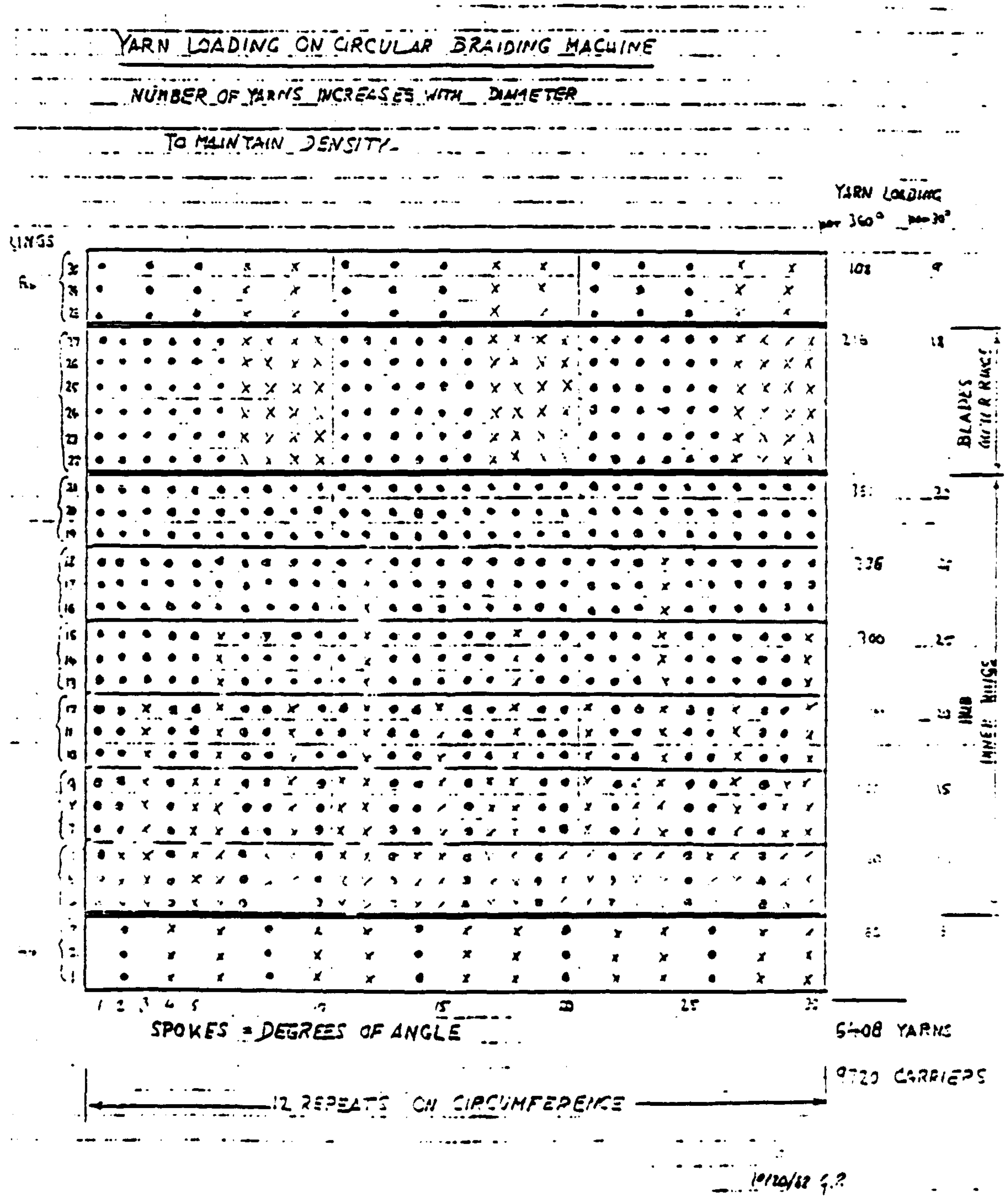
3.2 The loading of the number of yarns per ring is gradually decreased from a full loading at the outermost ring forming the hub (ring 21) toward the inside rings in order to maintain the same yarn density of yarns per inch. The proposed loading is shown in Figure XXVIII.

3.3 Based on this loading the total number or active (yarn carrying) elements is 6408.

3.4 The number of passive (no yarn carrying) elements is 3312.

Figure XXIX

Yarn Loading or Circular Braiding Machine



D. Design Considerations

1. The ultimate objective of this SBIR program is the establishment of a commercially applicable manufacturing technology to fabricate complex gas turbine wheel preforms reliably, at reasonable cost, and in quantity. This will require a machine capable of continuous operation at a commercially viable speed.

2. A continuous, automated production machine would require that each active element carry a supply of yarn and the necessary tensioning device. Using 2" by 2" elements the machine would require an outside diameter of 33 feet and the cost would far exceed the scope of a Phase II program.

It is furthermore advisable that experience be gained in braiding pattern requirements, loom operation, manipulation of this large number of fibers, yarn tension requirements, handling of brittle silicon carbide fibers, and the forming, handling, and matrix induction of silicon carbide preforms before committing to a continuous production machine.

Braidtech is committed and has begun an independent effort to build a continuous rectangular MAGNAWEAVE loom. The experience gained in miniaturizing yarn carriers, manipulating fibers, and operating the loom should be directly applicable to any subsequent construction of a circular continuous production machine.

3. An alternative approach is to use fixed length yarns of approximately 3 feet length which results in a machine with the following features:

3.1 The braiding length (equal to the thickness of the turbine rotor) is short, approximately 1", and therefore allows using fixed yarn lengths, since the yarn angle to the braiding point changes only minimally for the short braiding length.

3.2 The fixed length yarn is attached to an elastic thread of rubber band anchored to each active element. The rubber band provides the yarn tension.

3.3 The machine is designed for the same number of elements, but each element is greatly reduced in size and consists of a small slider 3/8" by 3/8" in cross section and 7/16" long with a pin protruding to attach the elastic band.

This arrangement dramatically reduces the size of the machine to an outside diameter of 7 feet. The smaller machine size and the replacement of bobbins with sliders reduces the cost of the mechanized fixed length machine to a fraction of the cost of a continuous production machine. The final product, however, should have the same quality and characteristics, as the braiding length is so short as to minimize the difference between fixed yarn lengths and continuous braiding.

4. In conclusion, it is a mechanized fixed yarn length, MAGNASWIRL machine that we propose to build for Phase II of this program. This is a prudent first step, given cost consideration, before construction of a continuous braiding loom. The design worked out during Phase I is specialized to function for the above-stated specifications. The automation is limited to specified movements and the present design does not provide for automated operation. Further study of other possible applications may make it desirable to incorporate a certain degree of flexibility beyond that provided for in this report.

5. Note that the design proposed above calls for 24 moving rings, and not the 18 rings specified for the generic turbine rotor shape. This resulted from machine design activities beginning prior to the specification of the Williams International 24-7 rotor as the model for the generic turbine rotor. Further, the decision to progressively insert axial fibers enabled a reduction in the number of rings at the specified fiber density. As machine design activities were already well underway, no effort was made to redesign the machine for the 18 moving rings now required (see IV C). Only minor cost savings would be anticipated by reducing the number of inner rings to conform with the new requirement.

E. Design Concept

Based on the motion requirements shown in Figure 3, the 24 moving rings are divided into two separate sets of rings: 18 rings moving 3 steps alternately in opposite direction for the hub, and 6 rings moving 1 step alternately in opposite direction for the blades.

To support and stiffen the rings as well as moving them together, all the rings moving simultaneously the same distance in the same direction are mounted by means of a common spacer (Figure XXIX) onto a ring-shaped plate below. To mount a set of rings two plates are required over the top of each other (Figure XXX). For mounting the rings on the lower plate, segment shaped cut-outs in the upper plate are provided at regular intervals. These cut-outs also have to allow clearance for the relative angle of motion between the plates.

With this arrangement, the two sets of rings require four ring shaped plates. Each plate is pivoted from the center of the machine with a ten-arm structure and a center bearing mounted on a common pin (Figure XXXI), plan view Figure XXXIII. The leveling of the plate is provided by a number of ball bearings or cam rollers located along the periphery of each plate. These bearings are mounted on the supporting structure and carry the weight of 7 plates. Figure XXXII shows the actual dimensions of this cross-section of the machine. Small air cylinders are located on the inside and outside of each of the

360 radial grooves through the 30 rings for pushing slider elements outward and inward. The support structure also carries air cylinders whose piston rods are connected to the four ring plates and provide the rotary actuation of the plates (Figure XXXIV). For each plate two cylinders are provided on diametrically opposite sides. All cylinders moving together at all times can be connected to a common valve. The solenoid valves are operated from manual switches for step by step operation. No automatic operation is planned but could be added. Since only 30 weave motions are required to braid a 1 inch thick rotor, the actual braiding time is a relatively small part of the overall time of the operation.

The entire structure is supported on a rigid base frame consisting of a welded structure of aluminum channels with support pads for the ten radial supports and center pivot as well as levelling pads for the frame set-up (Figure XXXV). The relative location of the supports, centering arms and tooling braces (described below) are shown in Figure XXXIV.

The overhead structure required to hold the braiding mandrel is shown in Figure XXXVI. For centering purposes this structure is connected to the base frame. A roll-away catwalk is provided for access to the mandrel.

Isotropic drawings of the circular braiding machine, its operation, and the ring mounting on rotating plates can be found in Figures XXXVII, XXXVIII, and XXXIX.

Figure XXX

Cross Section, Circular Braiding Machine

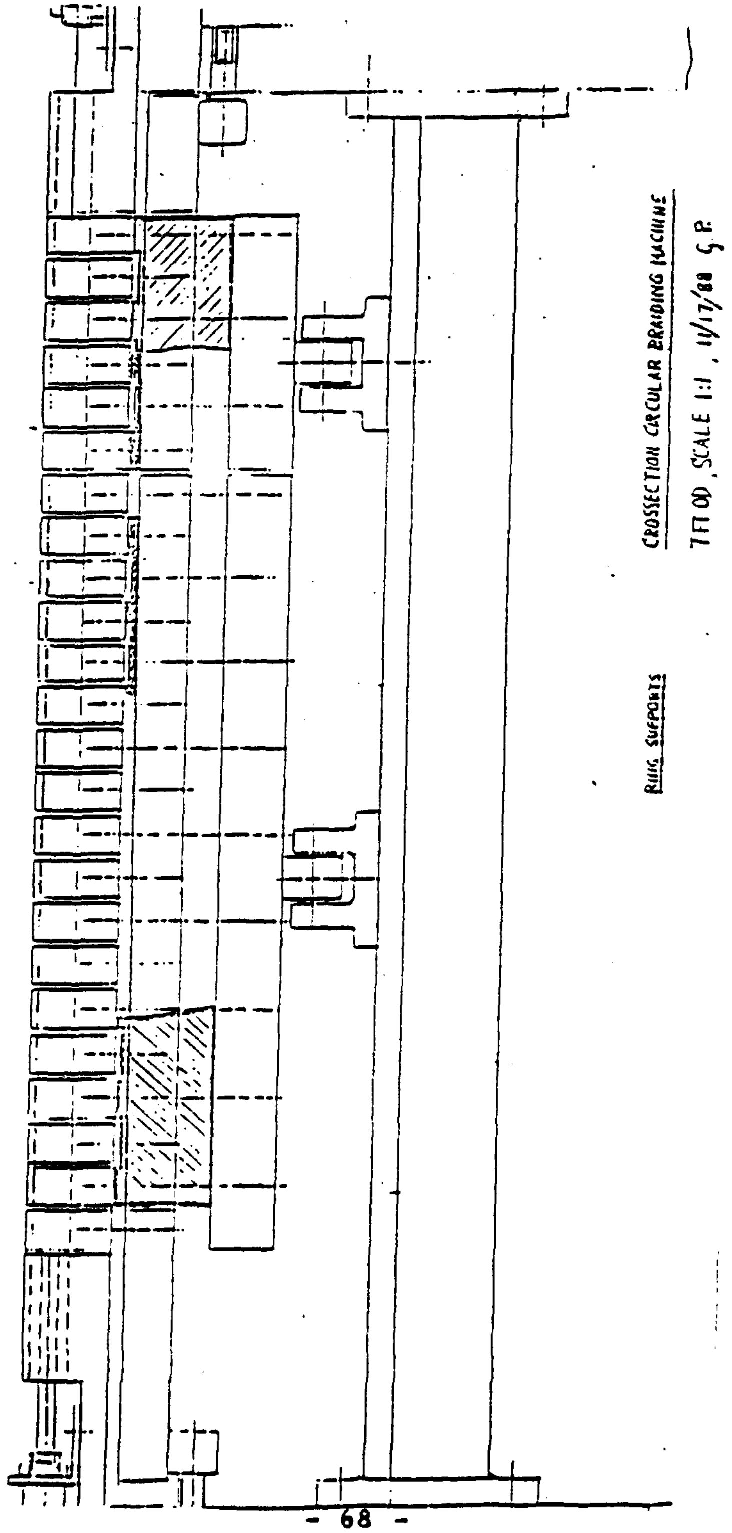
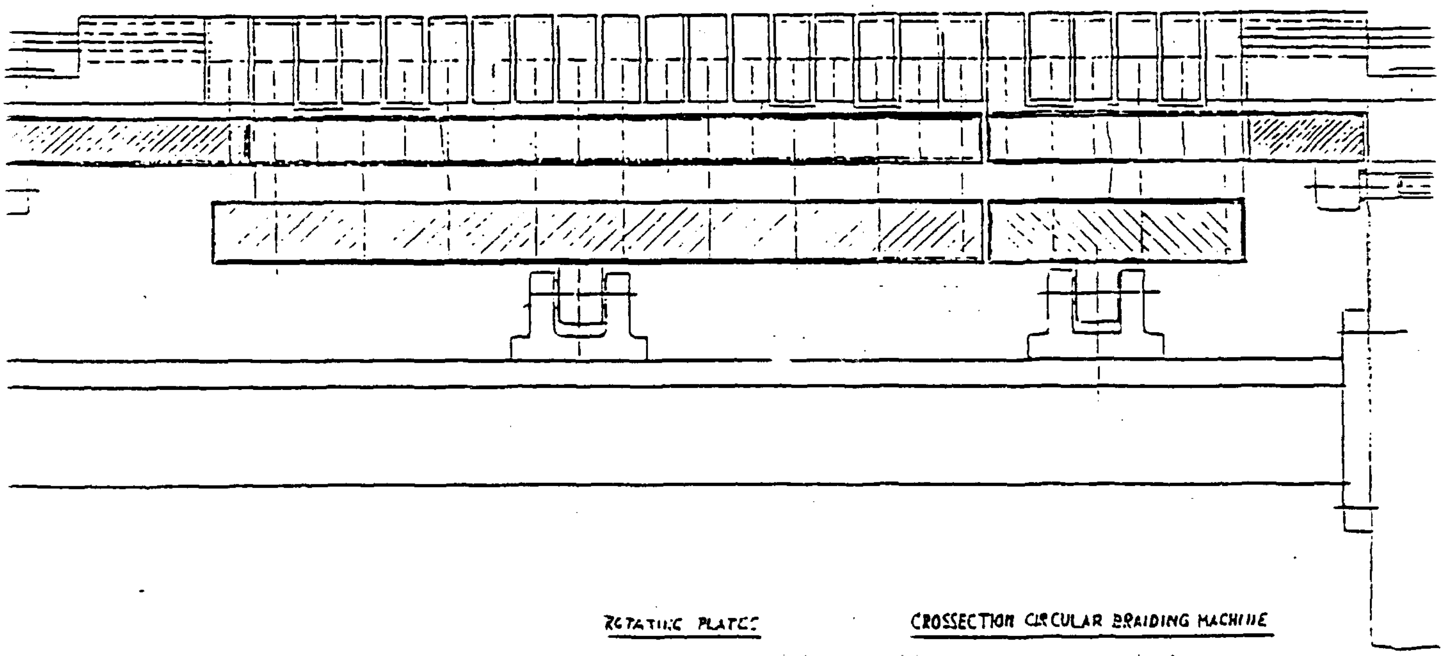


Figure XXXI

Rotating Plates



ROTATING PLATES

CROSSECTION CIRCULAR BRAIDING MACHINE

TFT OD, SCALE 1:1, 11/17/88 G.P.

Figure XXXII

Ring Centering Structures

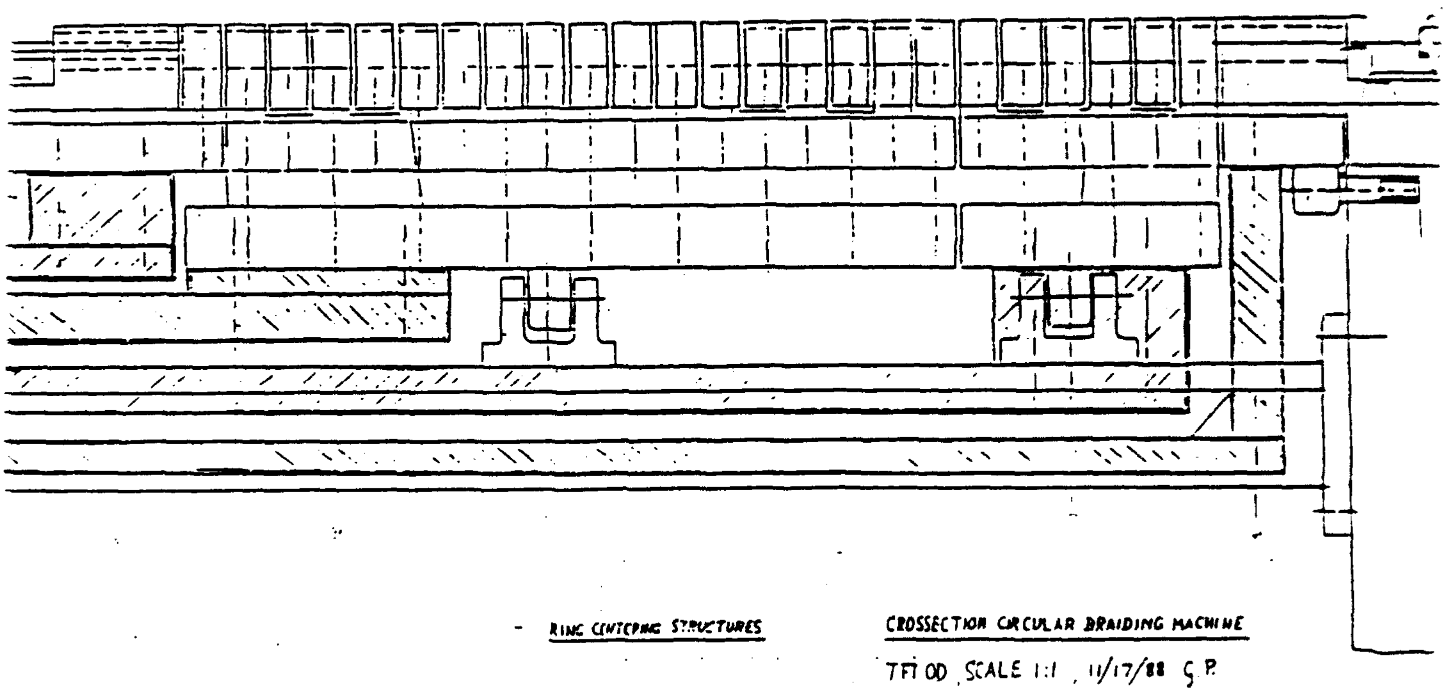


Figure XXXIII

Dimensions, MAGNASWIRL Machine

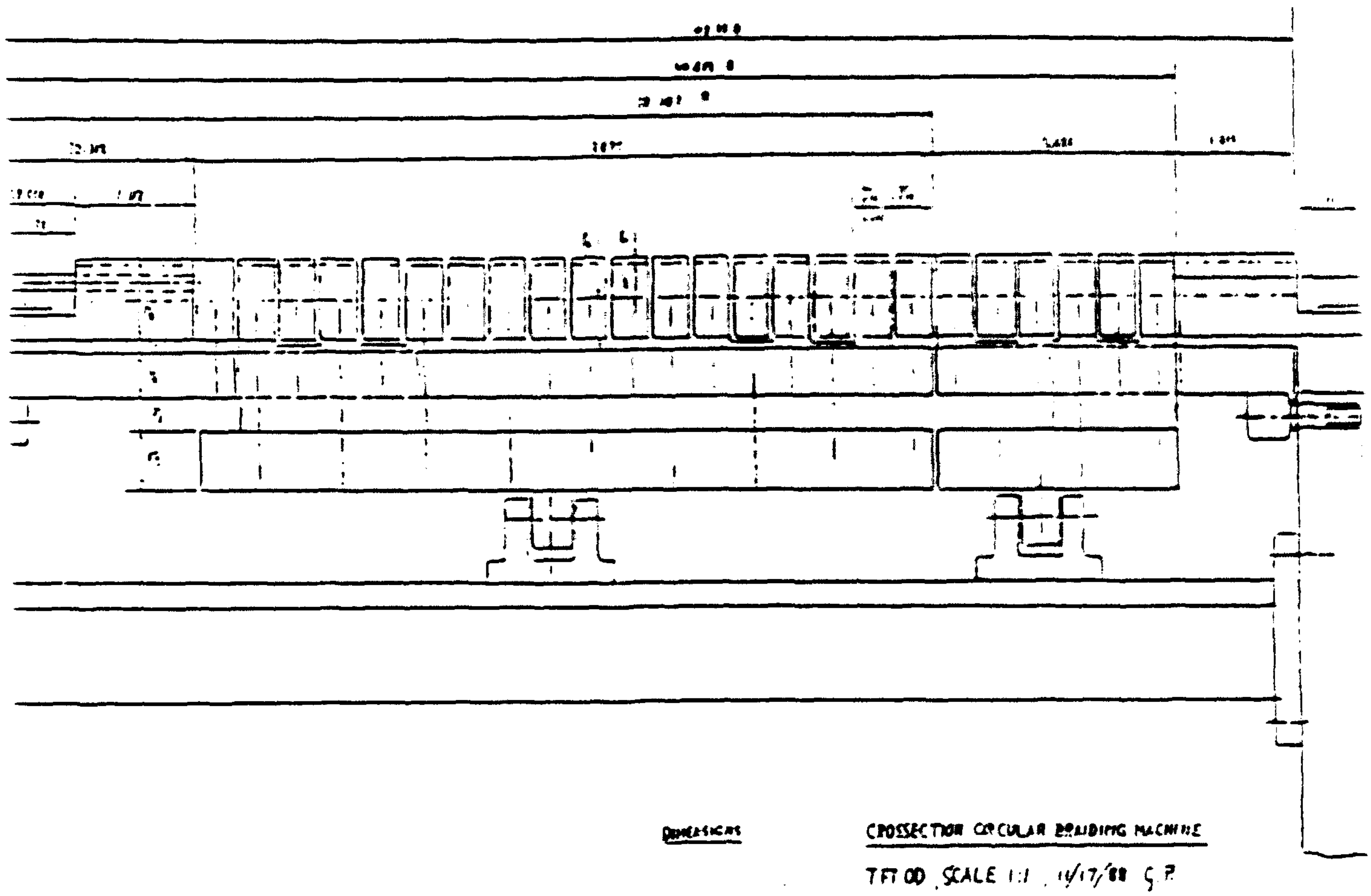


Figure XXXIV

Plate Support Structure

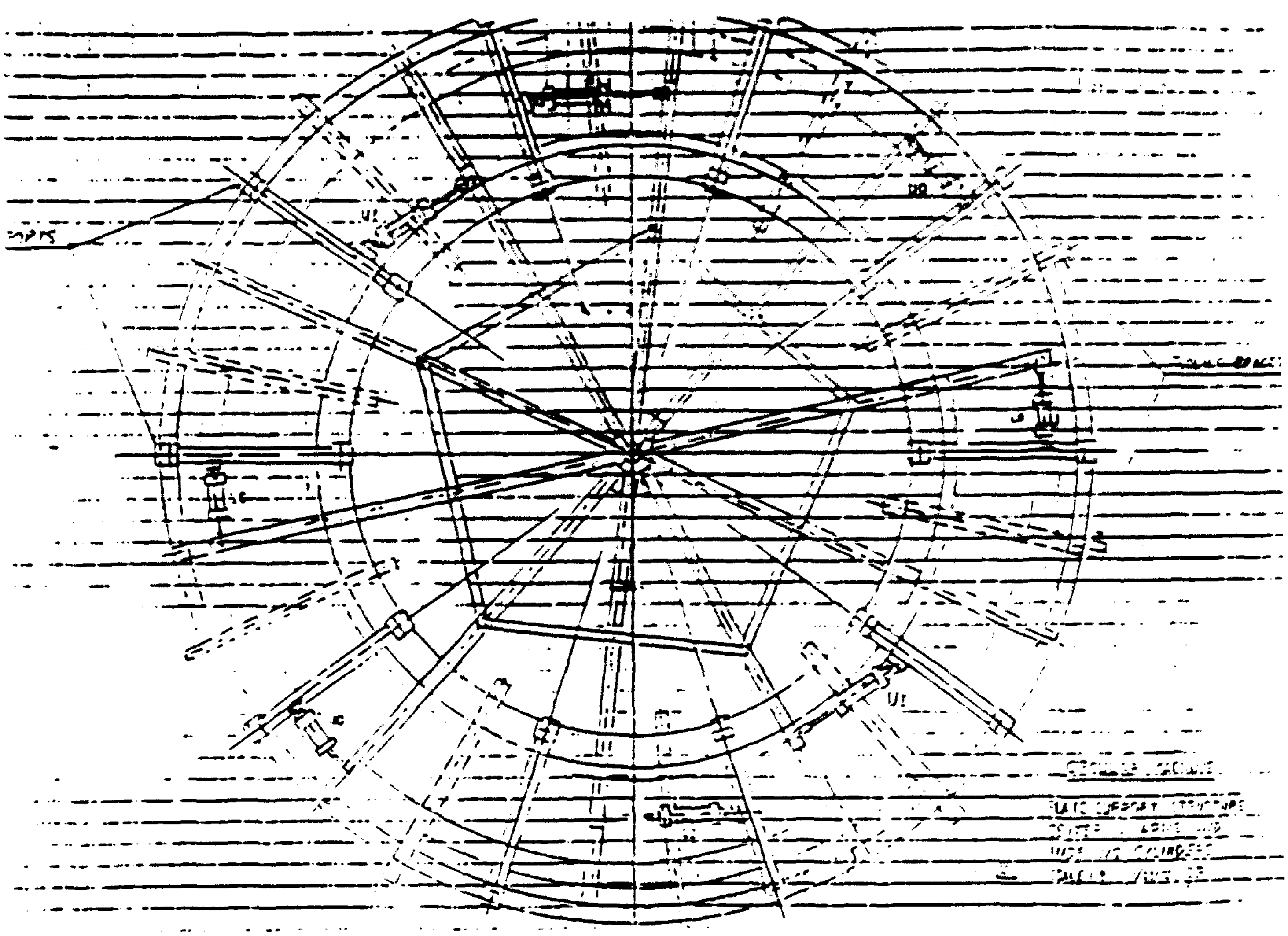


Figure XXXV

Base Frame, MAGNASWIRL Machine

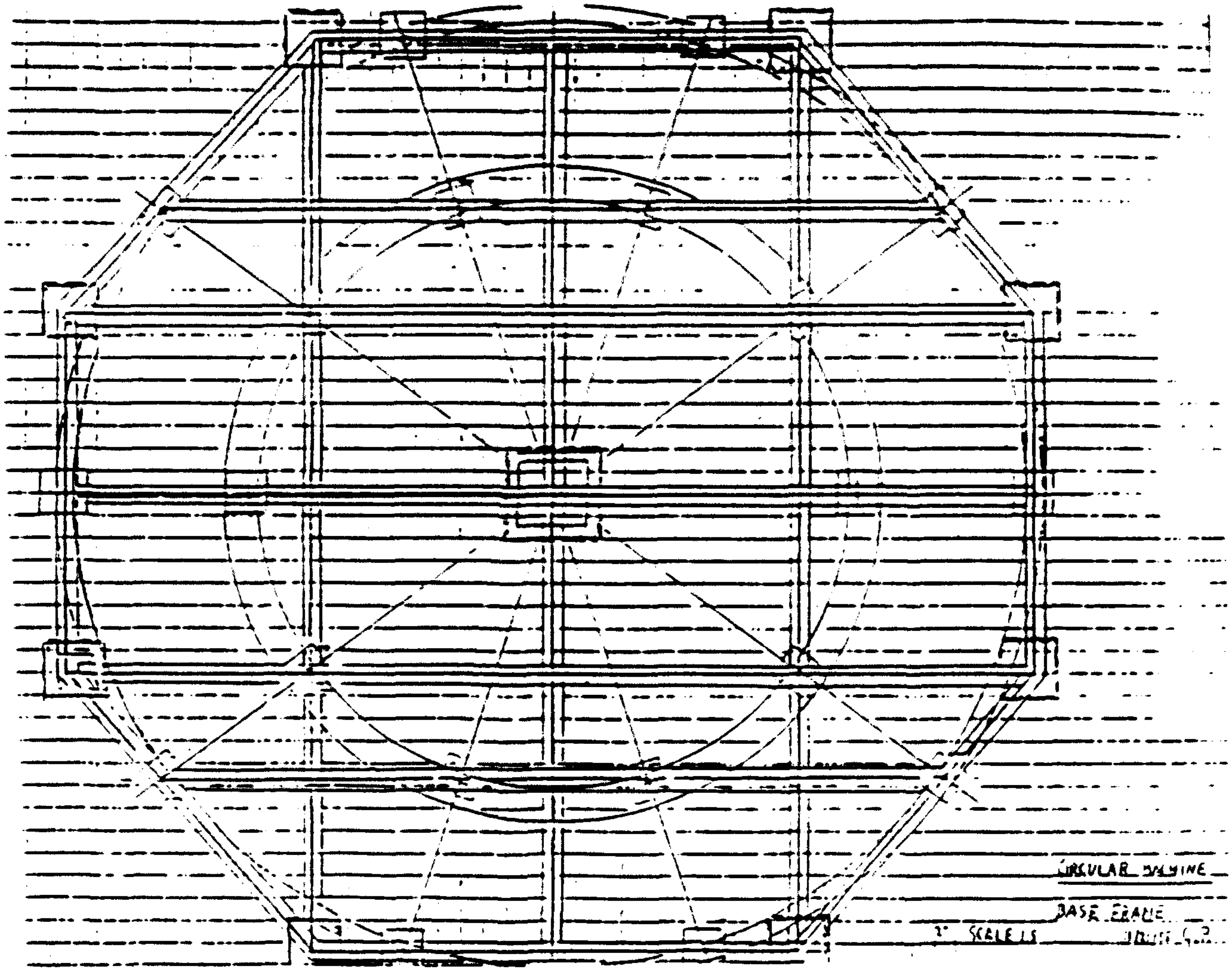


FIG 10

Figure XXXVI

Overhead Structure

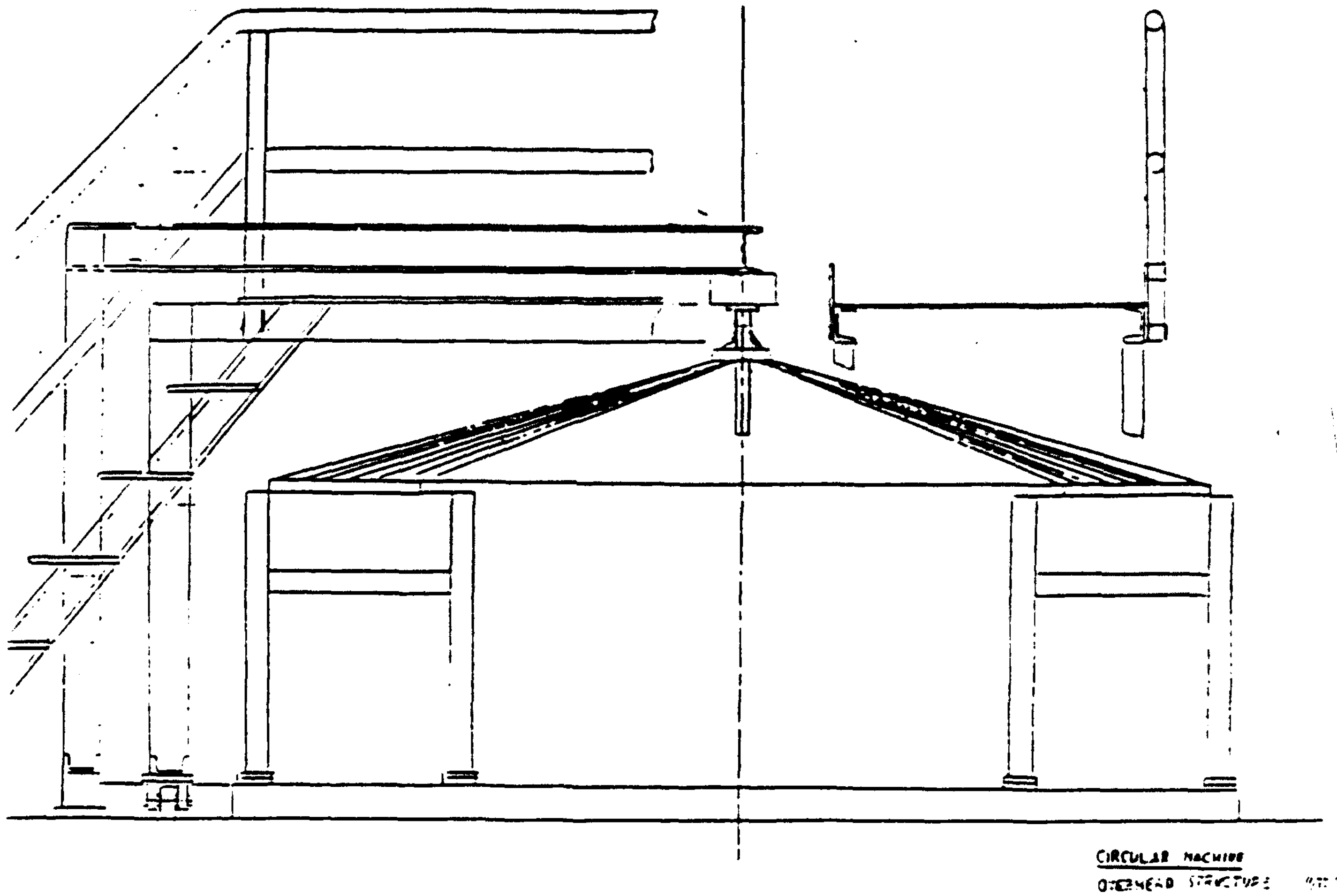


Figure XXXVII

Circular Braiding Machine

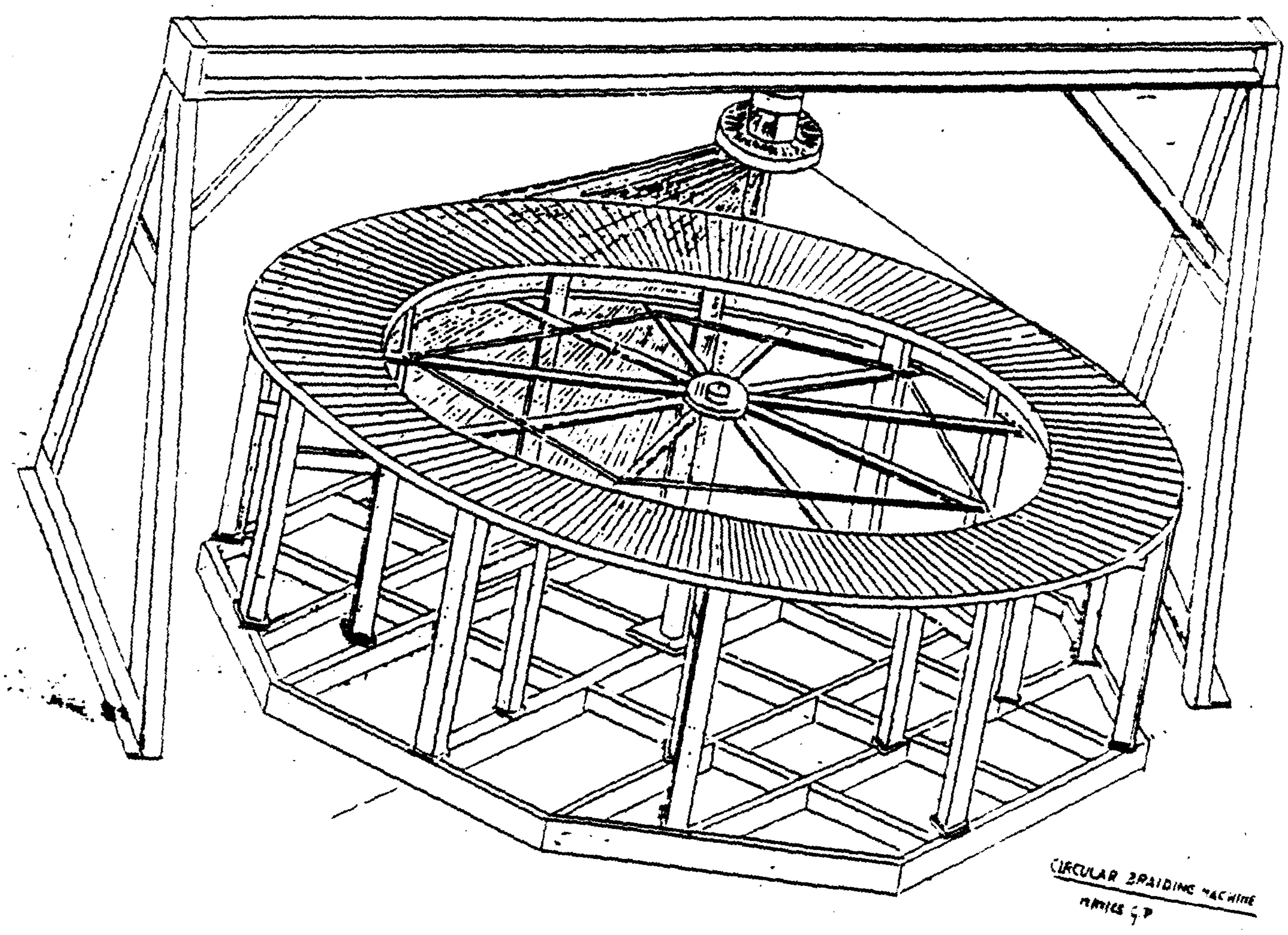


Figure XXXVIII

Circular Machine Operation

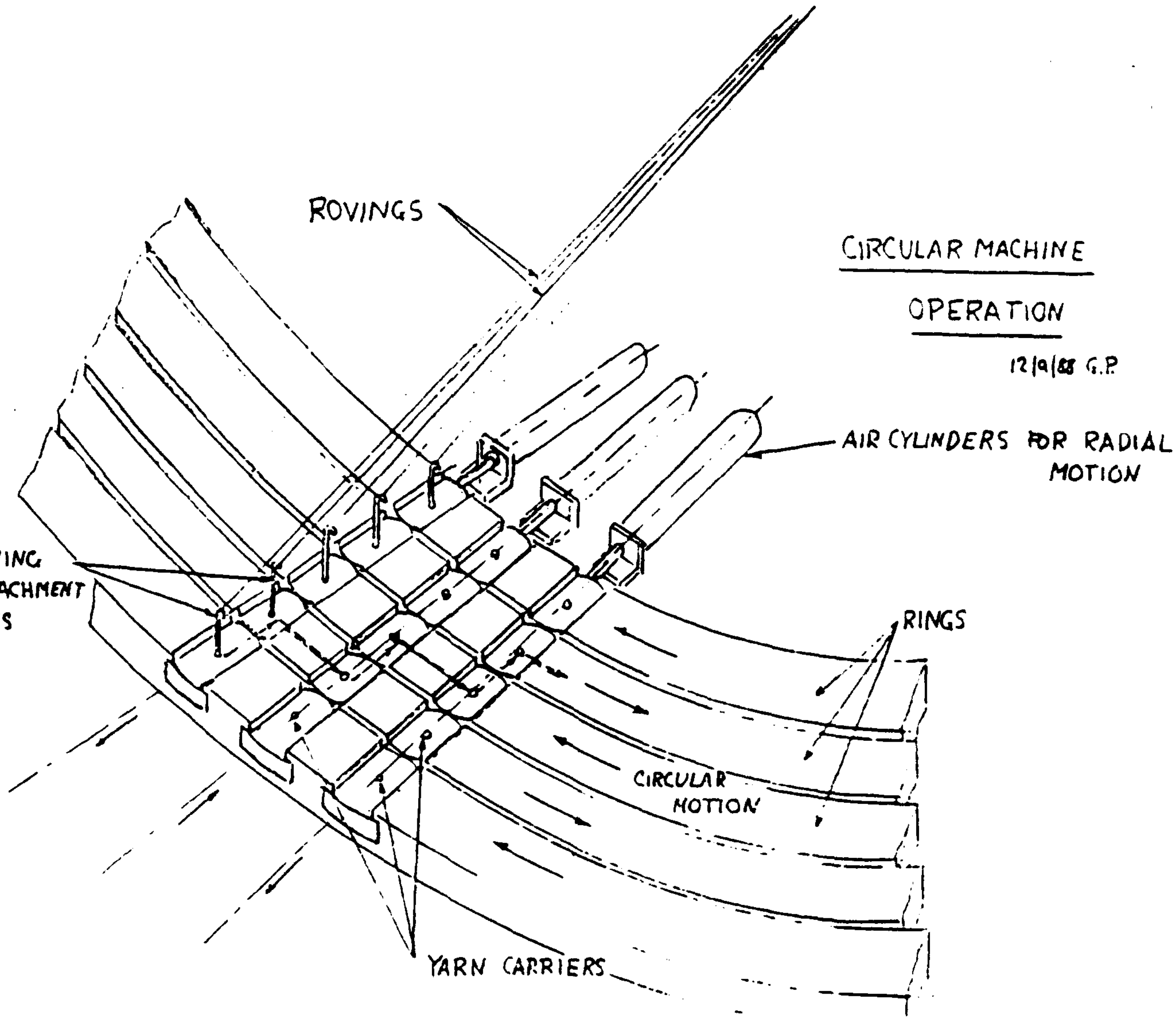
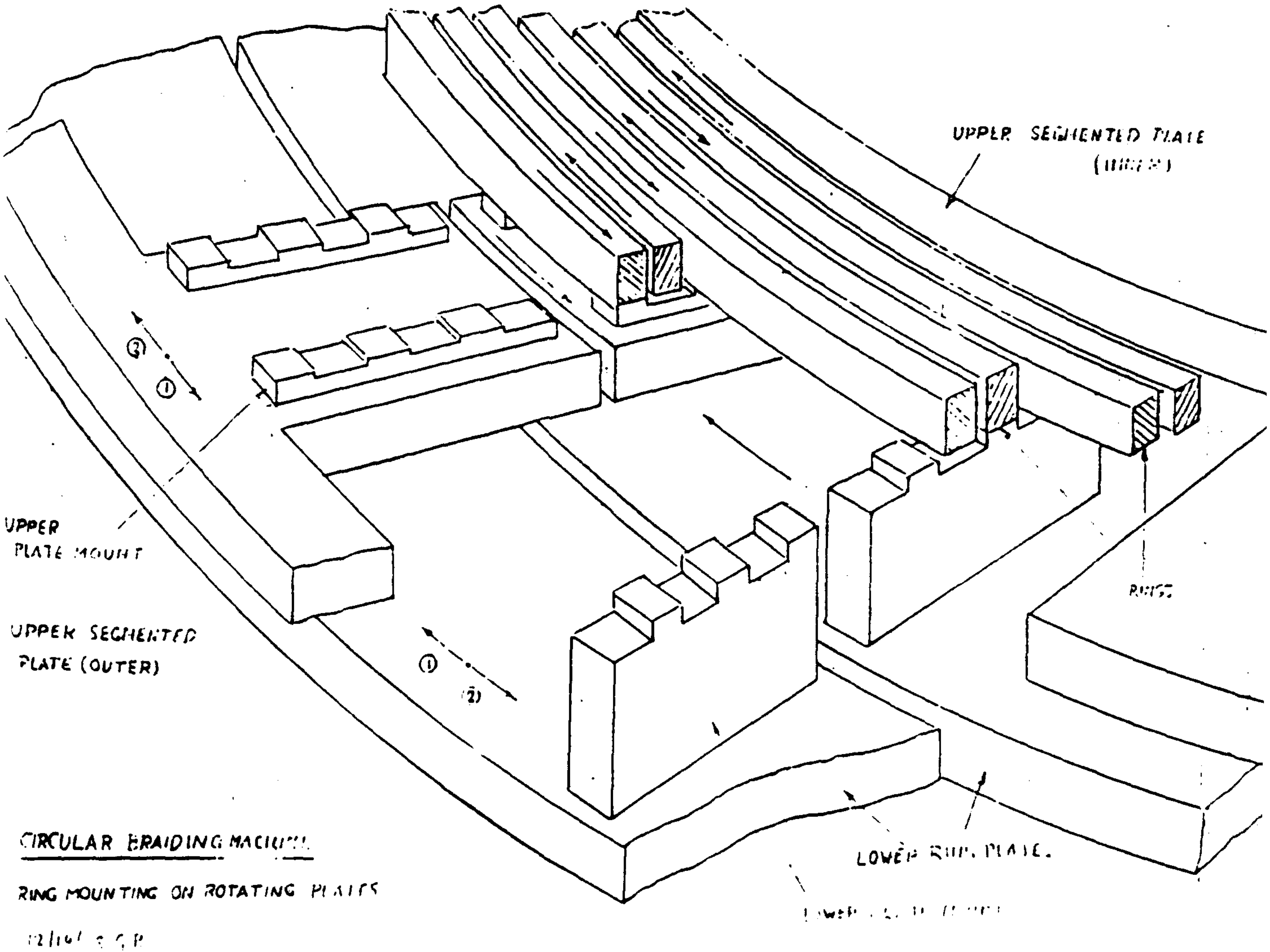


Figure XXXIX

Ring Mounting on Rotating Plates



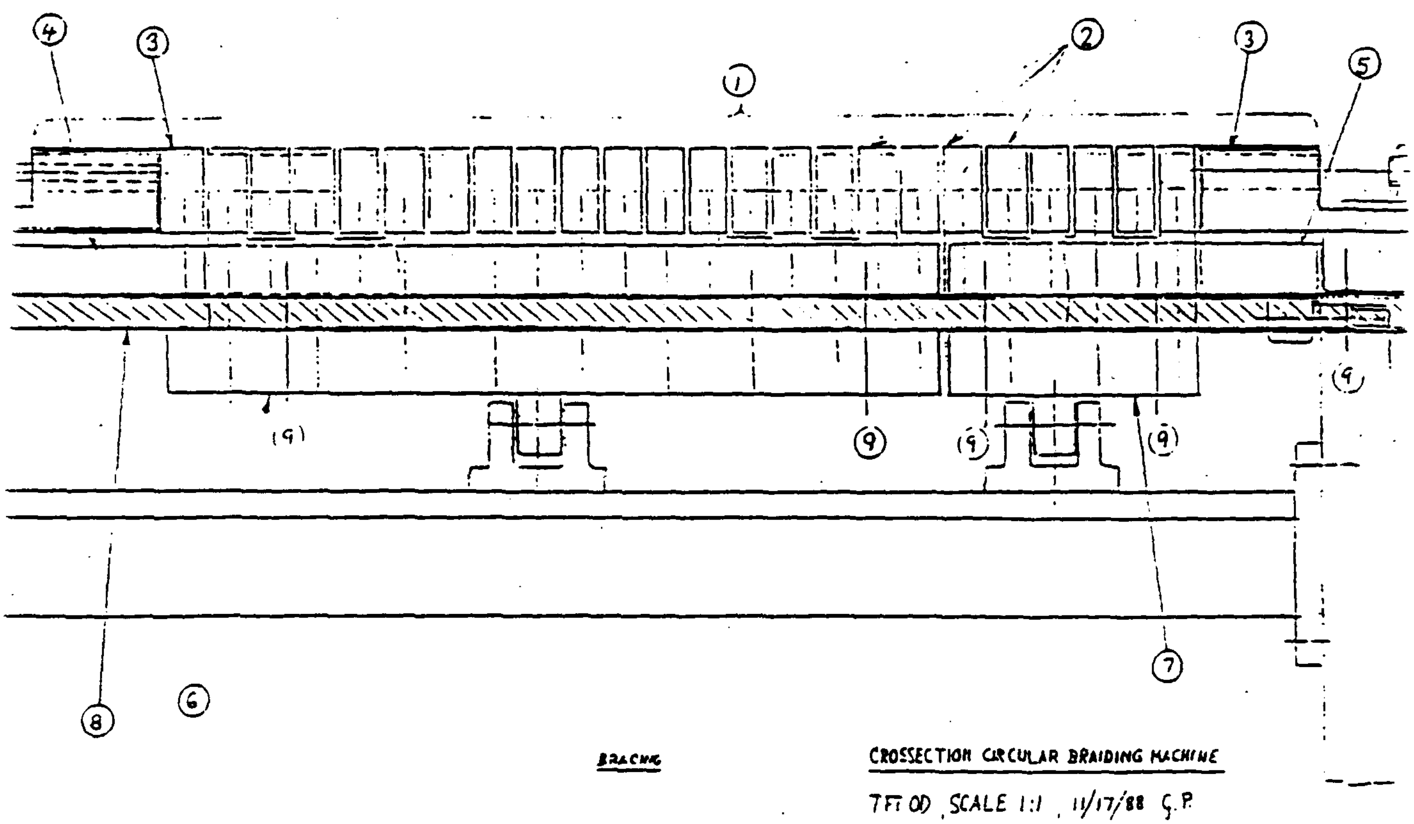
Manufacturing Considerations

The crucial factor for the successful operation of the machine is the precise location of the rings and the accuracy with which the radial slots in the rings line up. In order to accomplish this the following manufacturing procedure is being followed (see Figure XL):

1. A solid aluminum ring plate (1), later to be cut into 24 moving rings (2) and stationary ring sections (3), is machined to its final outer dimensions. Equally the support plates (4, 5, 6, 7) are finished machined including the segment cut-outs in the two upper plates (4, 5). In order to obtain the accuracy of ring location after ring separation, the future rings and stationary ring segments are bolted down on the support plates with the required spacers in their proper location before ring separation.
2. Since after ring separation the support plates are free to move against each other, tooling braces (8) are used at 10 places around the circumference to bolt the four support plates (4, 5, 6, 7) and the two stationary ring sections (3) together during machining.
3. The sequence of operation will be as follows:

Figure XL

Bracing



1. Align the finish machined ring plates (1, 4, 5, 6, 7) upside down, with plate (1) at the bottom and the ten tooling braces inserted concentrically with each other and drill and dowel the fastening holes to the braces (9) to establish their relative location.

2. Remove plates (6) and (7) and drill top on a large CNC machine the fastening holes between the upper plates (4) and (5) and plate (1).

3. Replace plates (4) and (5) with plates (6) and (7), using the brace holes for alignment reference and drill and tap the fastening holes between the lower plates (6) and (7) and plate (1).

4. Assemble (still in upside down position) plates (4) and (5) to plate (1), inserting the pre-machined and pre-drilled spacers (see Figure 5, ring supports).

5. Assemble to this assembly plates (5) and (7), inserting the proper spacers as well as the tooling braces. The five ring plates are now firmly assembled together.

6. Align and drill in sequence the four centering structures (Figures 7, 9) to the plates, starting with (4), then (6), (7), and (5) and using a common pivot for centering.

7. Assemble centering structures to the plate assembly. The weight of this assembly is about 600 lbs.

8. Turn the assembly right side up so that plate (1) is on top, place it on a carrousel machine and machine out the 25 concentric grooves to separate the rings.

9. Using a precision indexing table, the 360 radial grooves can now be milled out through the 30 ring positions. This completes the machining. The assembly is now held together by the tooling braces, and all the relative positions are maintained.

10. The plate assembly is now transferred on the assembled base and support structure, using the support roller adjustments for leveling.

11. Mounting supports for stationary rings are adapted, drilled and fastened.

12. Only now, after proper alignment, are the tooling braces removed, leaving the four support plates free to rotate.

13. The air cylinders and steps for radial and circumferential actuation can now be assembled.

The purpose of this manufacturing approach is to fasten the rings in their proper location on the machine before separation and maintaining them there as the best assurance to achieve the required precision.

VII. CONCLUSIONS

This Phase I project had as its technical objective to define a 3-D braiding machine with these capabilities:

- fabricate a variety of preforms
- exact fiber placement to meet property requirements
- fiber orientation capable of wide variation
- fabricate near net shape preforms
- automated process
- efficient in use of fiber
- shape capability must include complex geometries
- handle high modulus, brittle fibers with minimum damage, as a continuous economical process

The task list, identified in the proposal, generated a wealth of information that permitted the successful achievement of these technical objectives. In short, we have carried out that program plan, and have achieved results worthy of consideration of the continuation of this program into an expanded Phase II.

This final report provides complete details on the analyses conducted, the preliminary designs that have been generated to produce a 3-D braiding machine capable of meeting the shape and performance requirements defined as part of this Phase I project. The only modification to the original program plan is the interim step of substituting a mechanized, fixed yarn length machine for a continuous production machine.

Section VI of this report provides a preliminary design that satisfies the performance requirements of the materials designer. Interaction with the Air Force personnel, and the industrial participants in this industry have provided direction, and expressed their satisfaction that the approach is reasonable, the concept is feasible, and the return should be of exceptional value.

In consequence, Braidtech has investigated the effort required for Phase II effort that would generate, for evaluation, preforms of interest to the overall turbine engine program A Phase II proposal has been submitted.

Braidtech is pleased to commit itself to a continuing effort to bring this technology to the turbine engine market place, beyond the successful conclusion of Phase II.

FOOTNOTES

1. "Small Business Innovative Research Program", DoD Solicitation 88-1, (10-87).

2. Florentine, Robert A., "Turbine Engine Composite Preforms; Design of a MAGNAWEAVE Loom for 3-D Braiding Net Shapes", submitted by Braidtech, Inc., in response to DoD Solicitation 88-1(1).

3. Forscht, B.A., et. al., "Assessment of Carbon-Carbon Technology for Future Strategic and Tactical Missiles", Report ATC R-92000/0CR-76, Vought Corporation, for DARPA, Arlington, Virginia. (Order No. 4010). (12/80).

4. Private Communication, J. Halada, Williams International, Walled Lake, Michigan, to R. Florentine, Braidtech (8/88).

5. Private Communication, P. Draskovitch, Garrett Division, Allied Signal Corporation, Phoenix, Arizona, to R. Florentine, Braidtech (8/88).

6. Draskovitch, P., "High Mach Nonmetallic Turbine Engine Evaluation", request for quotation for USAF/POTC PRDA (8/88).

7. Florentine, Robert A., "MAGNAWEAVE- The Ultimate Reinforcement System for High Performance Composite Materials and Shapes", J. Industrial Fabrics, 1, 41 (1982).

8. Florentine, Robert A., "The MAGNASWIRL Process; MAGNAWEAVE Adapted for Axi-Symetric Composite Structures", Society of Manufacturing Engineers Conference, "Composites in Manufacturing 3", Jan. 1984. SME Em84-1000.

9. Ko, Frank K., "Tensile Strength and Modulus of a Three-Dimensional Braid Composite", Composite Materials, STP 893 (ASTM), Whitney, James M. ed., 1986.

10. Dow Corning technical literature on Nicalon Silicon Carbide Fiber, June, 1988.

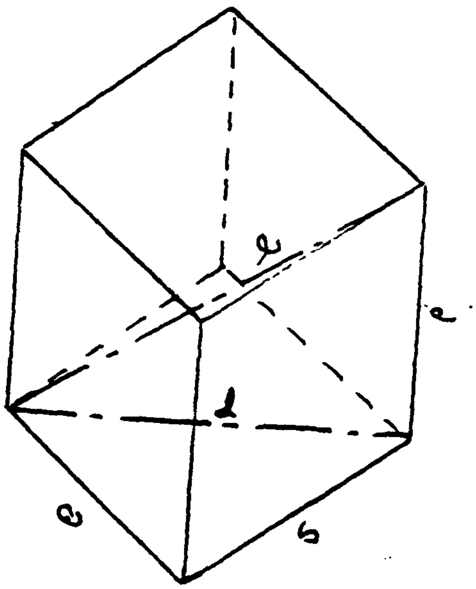
APPENDIX A

Definitions and Derivations

A. MAGNAWEAVE Weave Geometry - Definitions

The structure and properties of a 3-D braided preform are defined using the simple vector component results that derive from the "straight stick" model of the unit cell.

Figure I shows this model:



Definitions:

In developing the generalized form, the following definitions are involved:

1. a the fiber spacing in "row" direction
2. b fiber spacing in the "column" direction
3. c the "braid repeat" spacing, in the axial direction
4. d the diagonal formed by the a-b rectangle

$$d^2 = a^2 - b^2$$

5. e diagonal in the paralellopiped is the fiber direction

$$e^2 = a^2 - b^2 - c^2$$

6. V_f fiber volume
7. n_a fibers/inch in the row direction
8. n_b fibers/inch in the column direction.

B. Fiber "As Braided" Cross Section FAB

In calculating the loom loading, for a given fiber volume, one requires the "as braided" cross section. One recognizes that, oriented as the fiber is in the braid, the cross section of fiber that contributes to the fiber volume is that section cut through the fiber parallel to the plane of the loom.

In Figure I, FAB = fiber cross section (normal) x e/c

C. FAB-Integrated Area FAB_I

The effective cross section is the fiber "as braided" cross section plus that portion of the free area occupied by matrix.

In a given area formed by cutting the volume of the composite parallel to the plane of the loom (perpendicular to the axial direction of the braid):

$n_a \times n_b = \text{fibers/in}^2$

$(n_a \times n_b) \times FAB = V_f$

$n_a \times n_b = V_f/FAB$

and $\quad n_a = V_f/(FAB) \times n_b$

$\quad\quad n_b = V_f/(FAB) \times n_a$

If $n_a = n_b$, then

$n_a = n_b = (V_f/(FAB))^{1/2}$

D. Fiber Volume as a Function of Radius - Analysis

Loom geometry is selected by the outer radius of the part, weave geometry, and fiber volume. At that radius, the number of active elements/ring will produce a given fiber volume.

Within that radius, the fiber volume will increase. The current loom concept permits a reduction in the number of active elements per ring to adjust the fiber volume to the original value, at radii less than the outer radius.

The relationships derived below are useful in determining fiber volume anywhere in a part, and choosing the radii to change the number of active elements per ring.

Definitions

V_f	Fiber volume
V_{fR}	Fiber volume at a radius R
A_f	Area of a fiber in the part
A_{eff}	Area associated with a fiber, includes the non-fiber area
R	Radius in the part
C_R	Width the unit cell at radius R

Calculations

The area covered by the elements of a ring with a "design radius" of R_1 and N_1 elements per ring can be calculated to be:

$$\pi(R_1^2 - R_2^2) = N_1 A_{eff_1}$$

$$R_2 = R_1 - c_1$$

$$A_{eff_1} = c_1^2$$

$$\pi\left[R_1^2 - (R_1^2 - 2R_1 c_1 + c_1^2)\right] = N_1 c_1^2$$

$$\pi\left[R_1^2 - R_1^2 + 2R_1 c_1 - c_1^2\right] = N_1 c_1^2$$

$$2\pi R_1 c_1 - \pi c_1^2 = N_1 c_1^2$$

$$2\pi R_1 - \pi c_1 = N_1 c_1$$

$$N_1 c_1 + \pi c_1 = 2\pi R_1$$

$$c_1 (N_1 + \pi) = 2\pi R_1$$

$$c_1 = \frac{2\pi R_1}{N_1 + \pi}$$

$$V_{f_1} \times A_{eff_1} = A_{fiber}$$

$$V_{f_1} \times c_1^2 = A_{fiber}$$

$$c = \left(\frac{A_{eff}}{V_f}\right)^{\frac{1}{2}}$$

$$\left(\frac{A_{fiber}}{V_{f_2}}\right)^{1/2} = \frac{2\pi R_1}{N_2 + \pi}$$

$$\frac{A_{eff}}{V_{f_2}} = \frac{(2\pi R_1)^2}{(N_2 + \pi)^2}$$

$$V_{f_2} = \frac{1}{A_f} \frac{N_1^2 + 2N_1\pi + \pi^2}{4\pi^2 R_1^2}$$

A_f is constant for a given weave, and fiber diameter.

N is much greater than

So, $N_1^2 + 2N_1\pi + \pi^2 \sim N_1^2$

and $$V_{f_R} = \frac{N_R}{4\pi^2 R^2}$$

$$\frac{V_{f_{R_1}}}{V_{f_R}} = \frac{N_{R_1}}{4\pi^2 R^2} \times \frac{4\pi^2 R^2}{N_R}$$

$$V_{f_{R_1}} = \frac{V_{f_R} \cdot N_{R_1} \cdot R^2}{N_R \cdot R_1^2}$$

for a constant N_R

$$V_{f_{R_1}} = (V_{f_R})(R^2) \times \frac{1}{R_1^2}$$

The radius when $V_{f_{R_1}} = V_{f_{R_1}}$

$$N_R = \frac{N_{R_1} \cdot R^2}{R_1^2} \quad , N_{R_1} = \frac{N_R R_1^2}{R^2}$$

$$\frac{N_{R_1} \cdot R^2}{N_R \cdot R_1^2} = 1$$

$$R_1^2 = \frac{N_{R_1}}{N_R} \cdot R^2$$

$$R_1 = R\sqrt{\frac{N_{R_1}}{N_R}} = \frac{R}{N_R}\sqrt{N_{R_1} N_R}$$

APPENDIX B

Maintaining Fiber Volume in a Circular Part

Inherently a circular braider, involving numerous rings which all contribute to the wall thickness of a part, will, if loaded uniformly in terms of elements/ring, produce a part with progressively decreasing fiber volume as one moves from inner to outer wall. Various attempts are made to smooth that change:

1. Periodically increase the number of elements. This produces a discrete change in fiber volume -- a sudden jump from a lower level.

2. Change fiber bundle size at various wall depths. This involves complicating the loom motion, and produces a similar decrease in fiber volume with radius, although on a lower scale.

A novel approach presents itself, given a system which contains a number of active elements/ring, in which not all elements are active.

Consider a loom loading where the desired fiber volume is calculated for the design diameter of the part. Moving inward, the fiber volume will increase, if the number of active elements remains the same.

Previously, we have attempted to smooth out the increase in fiber volume by a drastic, discrete decrease in the number of elements active in a ring. This gives a spiked fiber volume across the wall.

Suppose, instead of that sudden and considerable change in active elements/ring, we added elements or took them away, on a ring by ring basis. As the radius decreased, we would calculate the number of active elements required per ring to maintain the fiber volume at its original level. That would dictate how many active elements would be removed from the lower ring. As we proceed inward, more active elements are eliminated, and the fiber volume stays relatively constant across the wall.

Originally, some reservations would arise:

1. <u>What happens to the weave?</u> Actually, the weave is carried out by elements, active or passive, moving in the machine. An inactive element doesn't put a

fiber in the braid, thus reducing the number of fibers, but that is what is desired. How that deduction affects part properties should be investigated.

2. <u>What happens to the properties?</u> I expect little change. Instead of an increasing fiber volume, making infiltration difficult, and thus reducing part properties, the fiber volume is maintained fairly constant, making for a more homogeneous part. Certainly, this aspect must be investigated. Its advantage cannot be minimized.

3. Indeed, part properties across the wall should by having the fiber volume kept constant, eliminate or minimize the effect different fiber volume would have on thermal expansion, stiffness, etc., making for a part less likely to provide poor performance because of material mismatches.

The following is a specific example of the decrease in the number or elements with decreasing radius to maintain constant fiber volume.

Fiber volume: 0.4
Elements/ring 360
Active elements: 360

Ring	Radius	N_R	Delta Elements
R	2.013	360	0
R_1	1.908	342	-18
R_2	1.803	324	-36
R_3	1.698	306	-54
R_4	1.593	288	-72
R_5	1.488	270	-90
R_6	1.383	252	-108
R_7	1.278	234	-126
R_8	1.173	210	-144
R_9	1.068	188	-162
R_{10}	0.963	180	-180
R_{11}	0.858	161	-198

APPENDIX C

Introducing Fibers Step-Wise

A. Non-Participatory Insertions

To prevent the inserted fiber elements from participating in the braiding construction, the elements in the fixed rings above and below the inserted fibers are filled with empty elements; they do move radially when the braiding takes place.

The result is a unidirectional set of fibers through and around which the braiding fibers travel. The skeleton has an increased stiffness and strength because of the unidirectional character of so many of its fibers.

B. Participatory Insertions

If the stationary rings are filled as for a full 1 x 3 motion, across the entire circular loom, with alternating rings moving in opposition, then all the elements participate. The motion continues to be three elements/ring in both clockwise and counterclockwise manner, so the original loom loading of 120 elements/ring continue to do the original braiding. In addition, the additional elements begin to make a congruent braid within the original braid.

C. Progressive Insertion

A third approach to maintaining fiber volume with minimal change as the radius in the part increase is the concept of progressive insertion. This approach differs from random insertion in the fact that the elements added with increasing radius are inserted in spokes that may or may not participate in the braiding process.

a. Non-participatory elements will provide maximum stiffness in the fiber direction (radial predominantly), while being embedded as individual fibers in the overall braided skeleton.

b. Participatory elements are placed in selected spokes which will enter into the braiding operation, in some fashion. These fibers will be more firmly anchored in the skeleton, but will contribute less to the radial strength and stiffness than would the unidirectionals in the non-participatory instance.

The approach is the same for both concepts, and is based on the desire to maintain fiber volume constant across the wall of a part, even through radial increases require more fibers/ring to maintain fiber volume constant.

Making use of Table VII in section IV, we can conduct an exercise demonstrating each of these concepts.

<u>Loom Loading by Ring</u>

In the examples, we shall take as the criteria, Case IV of Table VII. In that case,

Fiber volume:	0.25
Fiber count:	1265
Design diameter:(ID)	0.665
Spoke length/element:	0.105
Rings (total):	24
Rings (mobile):	18

If we maintain the number of elements/ring in the blade area, 360, the number of active elements at the inner diameter is:

$$\frac{1.330}{4.025} \times 360 = 120$$

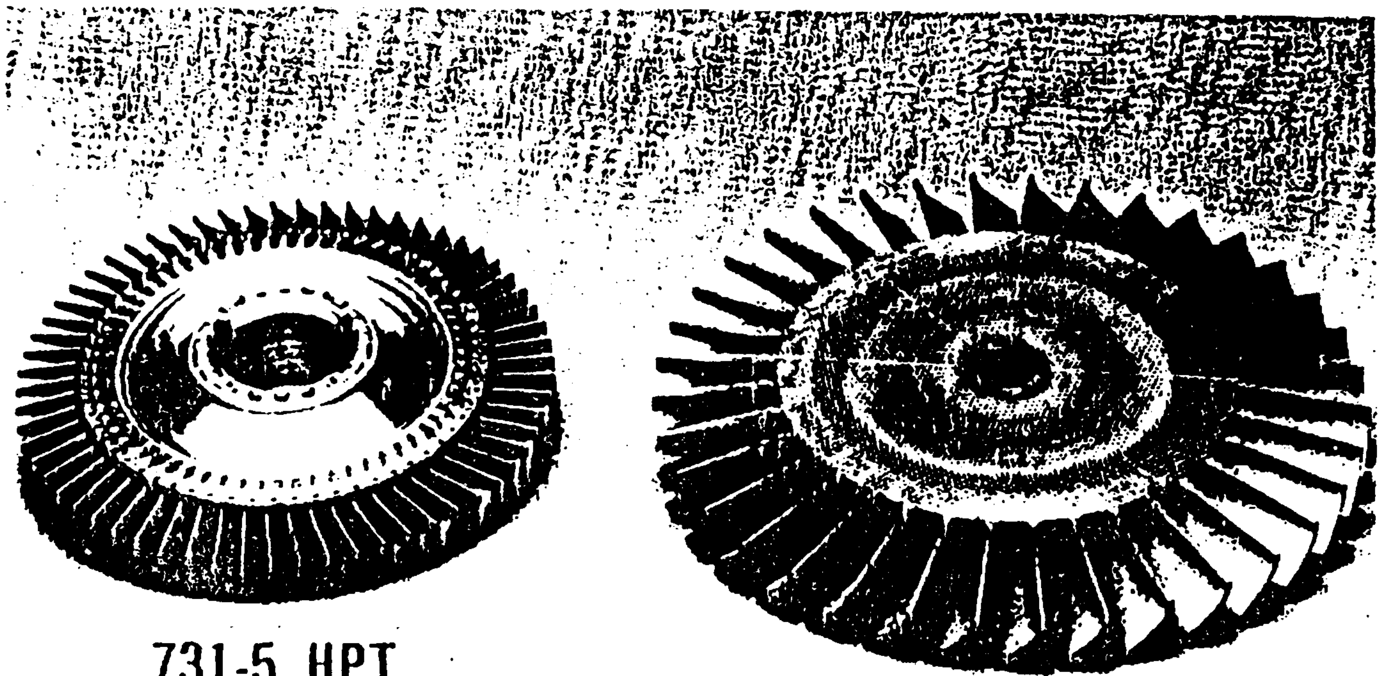
Therefore, the inner mobile ring, here chosen as R_4, will have 120 active elements.

APPENDIX D

<u>Other Candidate Shapes</u>

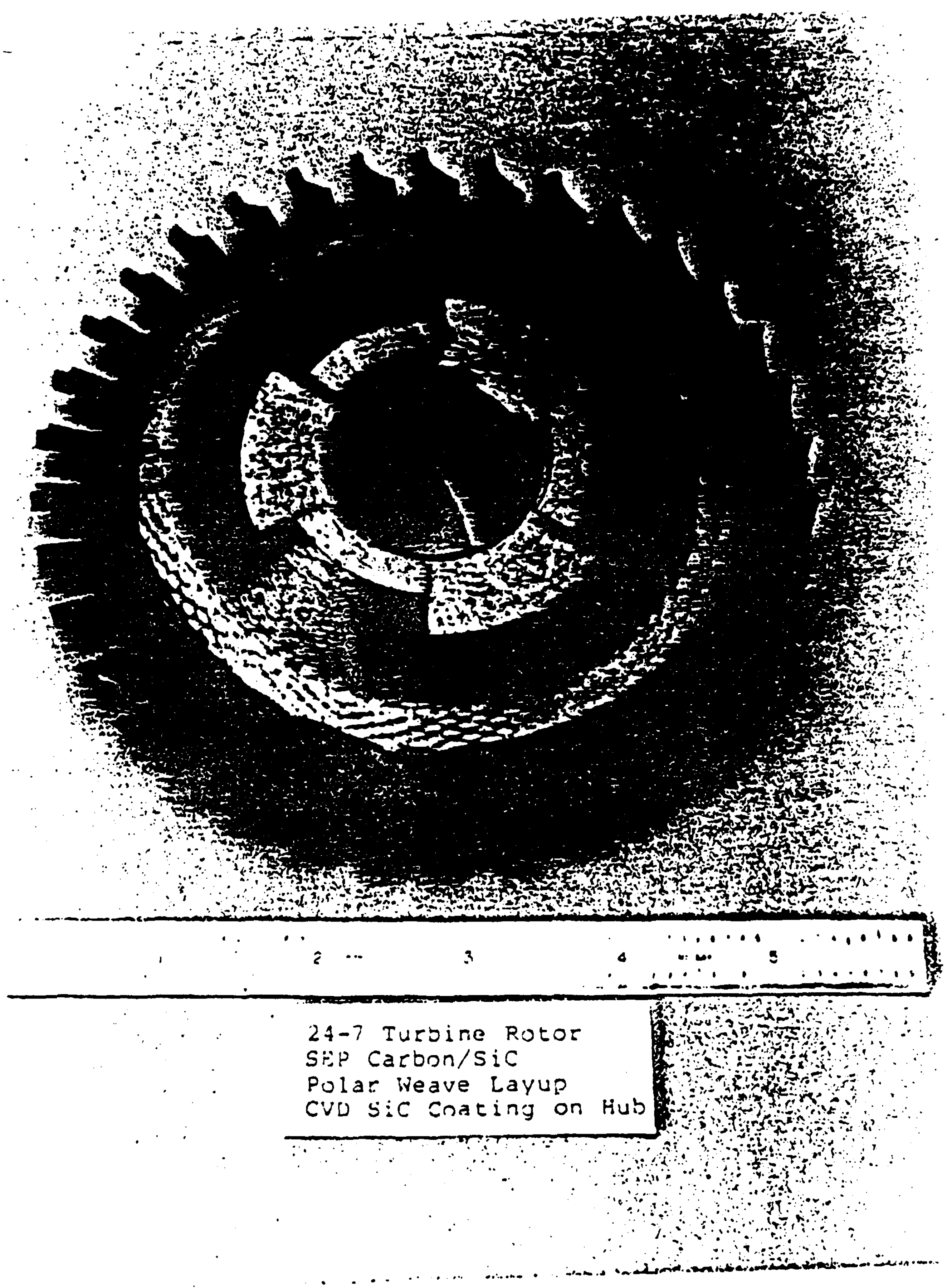
1. Elite C-C Rotor
2. 24-7 Turbine Rotor SEO Carbon/SiC, Polar Weave
3. 2D Quasi-Isotropic Layup Turbine Rotor
4. Typical Mixed Flow Compressor
5. Vought Turbine Wheel (1981)
6. Air Foil Dimensions
7. Computer Sketch of MAGNAWEAVE air-foil preform
8. Loom Loading for Air-Foil
9. Stress Distribution

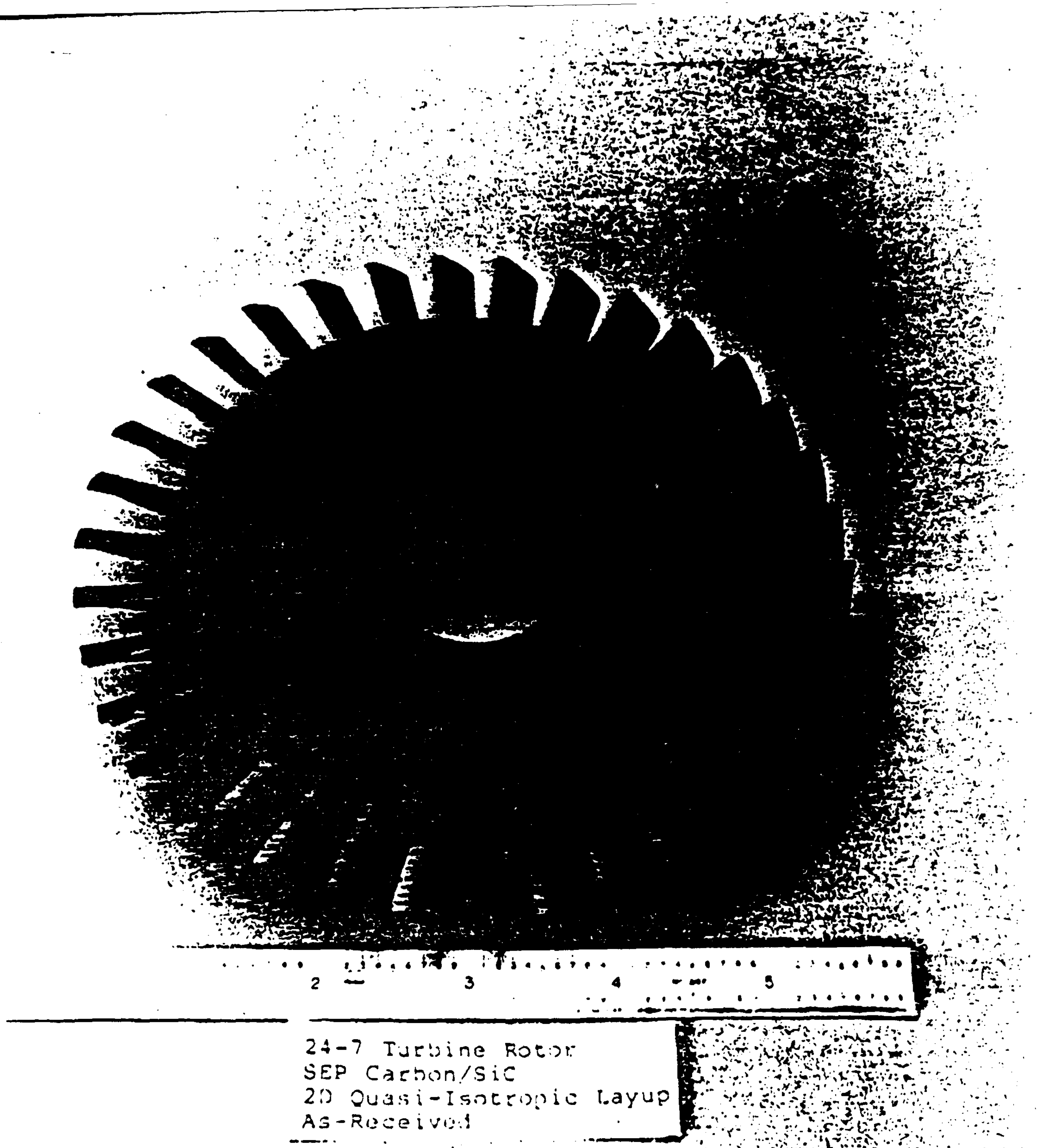
ELITE C-C ROTOR IS OVER 14 INCHES IN DIAMETER



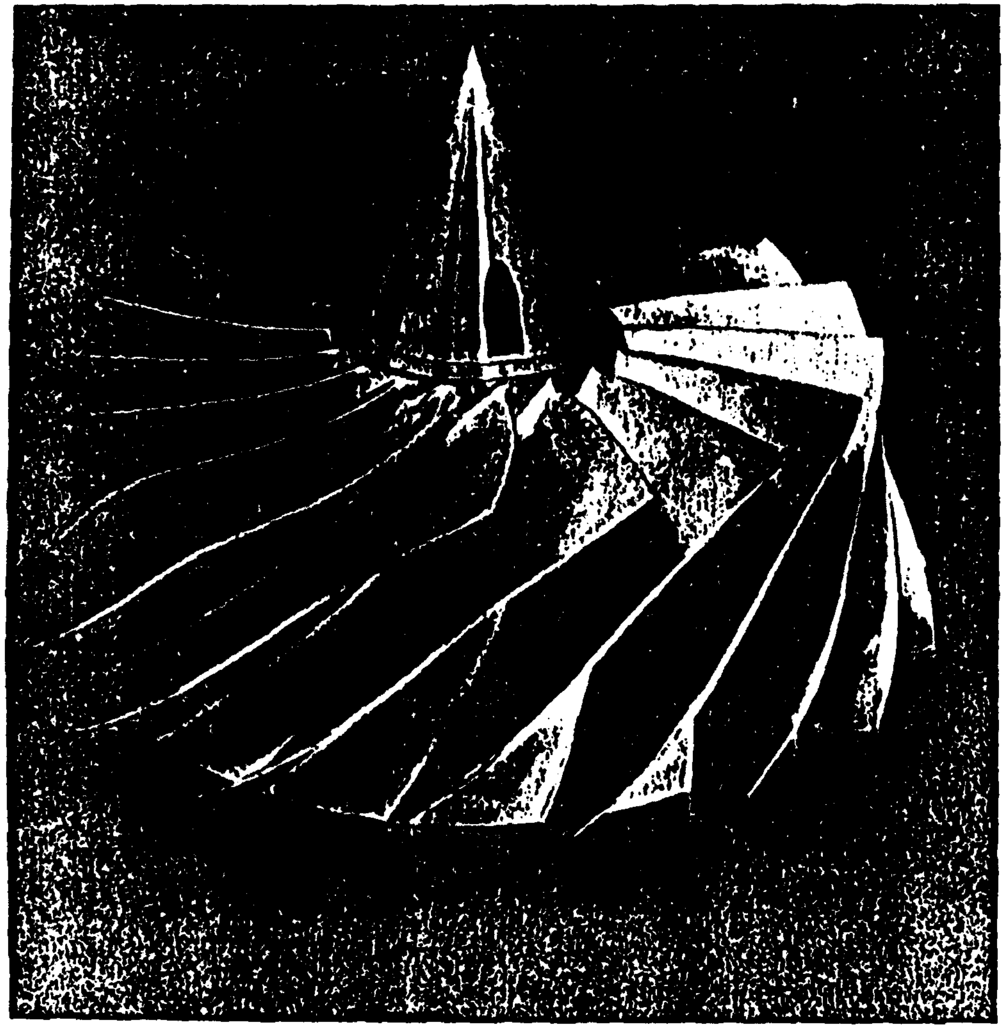
731-5 HPT

ELITE WHEEL


2
3
4
5
24-7 Turbine Rotor
SEP Carbon/SiC
Polar Weave Layup
CVD SiC Coating on Hub


2 3 4 5
24-7 Turbine Rotor
SEP Carbon/SiC
2D Quasi-Isotropic Layup
As-Received

Typical Mixed Flow Compressor

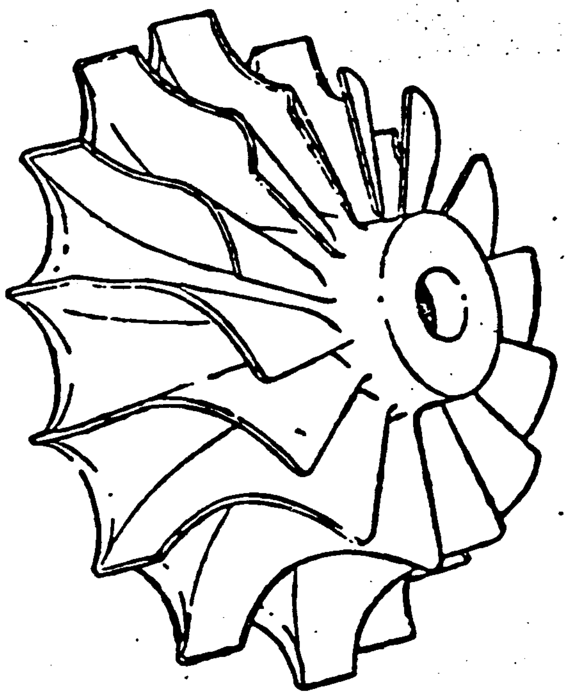


Allied-Signal Aerospace Company

Garrett Engine Division
111 South 34th Street
P.O. Box 5217
Phoenix, Arizona 85010

Allied Signal

TURBINE WHEEL



~~FIGURE VII~~I - A COMPLEX MAGNASWIRL SHAPE
INTEGRALLY WOVEN AS A SINGLE PIECE

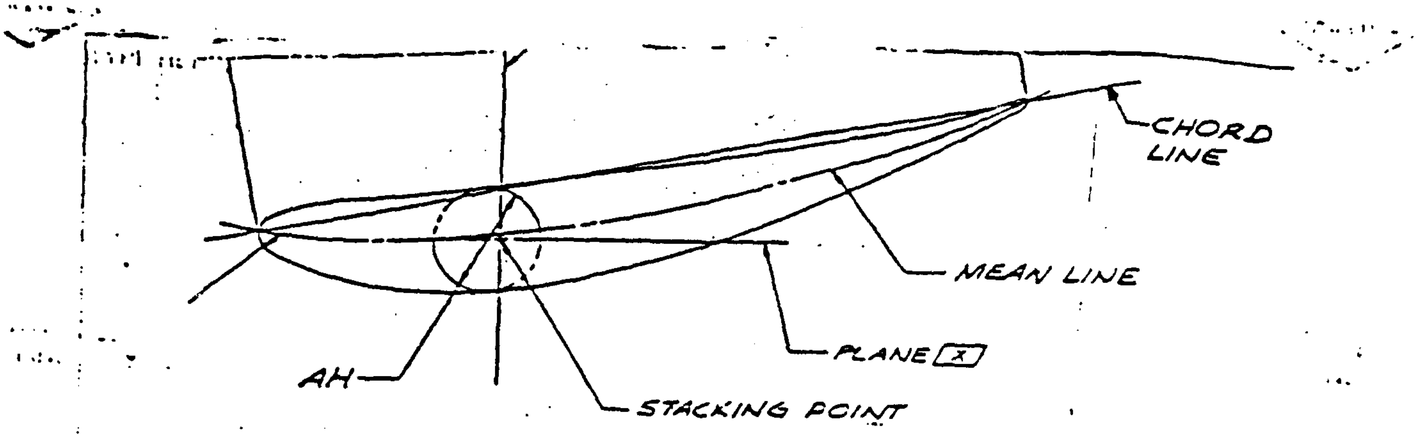


Figure 1

Typical Airfoil Section

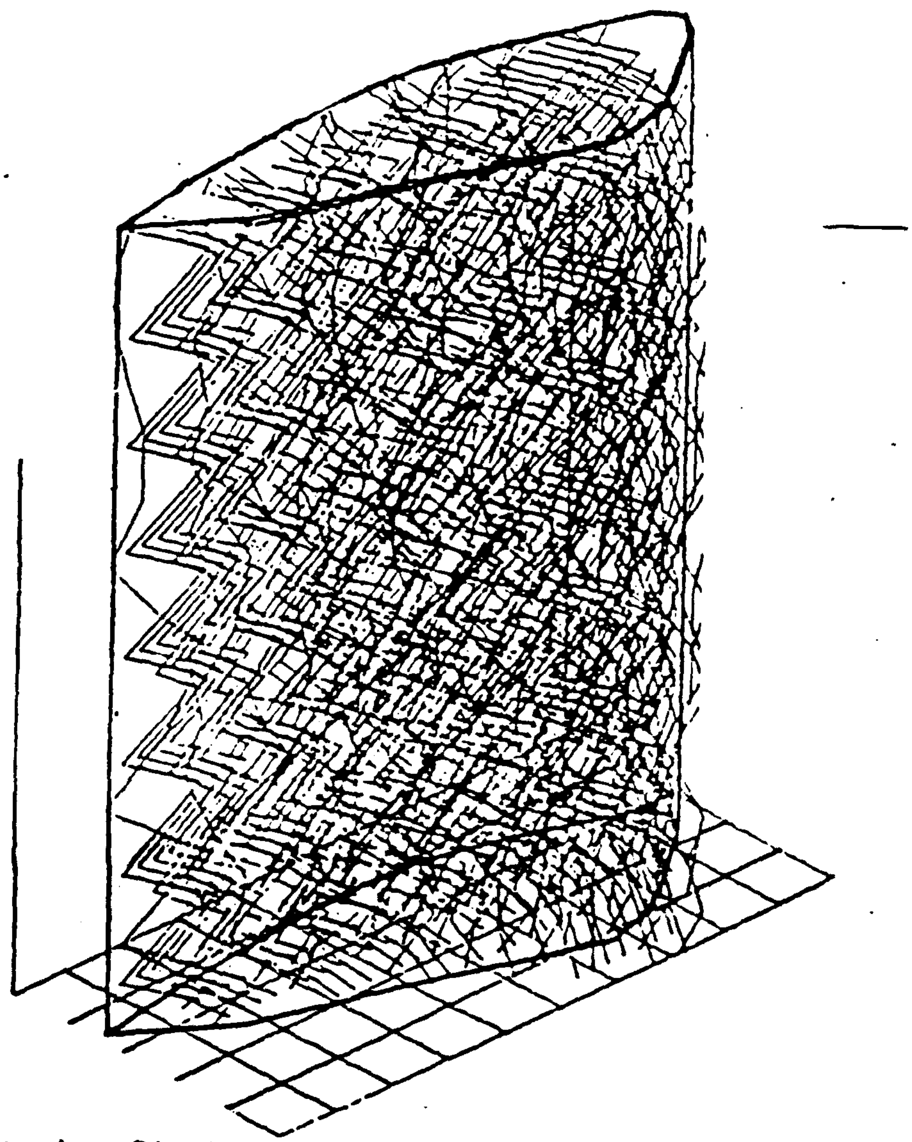


Figure II. Computer Simulation of 3-D Braided Preform for Air Foil Cross Section

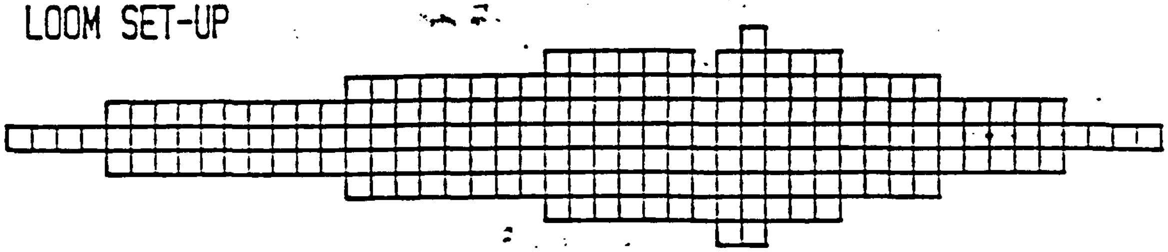
DEVELOPMENT OF 3-D FABRIC AIRFOIL

MATERIAL: CELION 12K

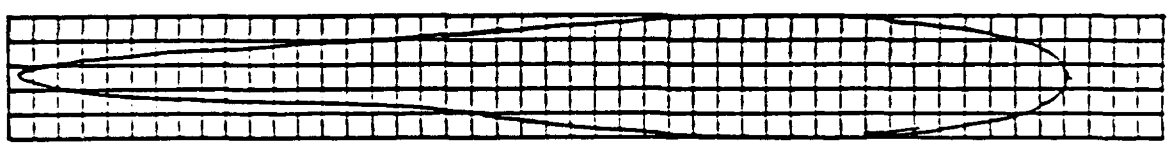
TOTAL NUMBER OF YARNS: 240 x 4 ply

TOTAL NUMBER OF BOBBINS: 240

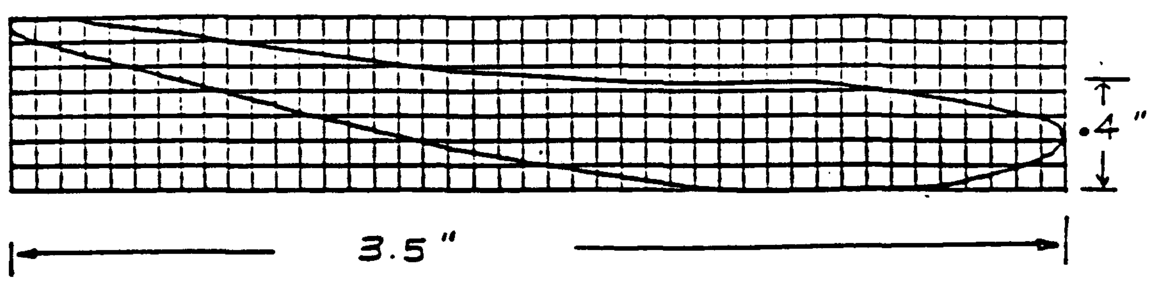
LOOM SET-UP



LOOM STATE FABRIC SHAPE

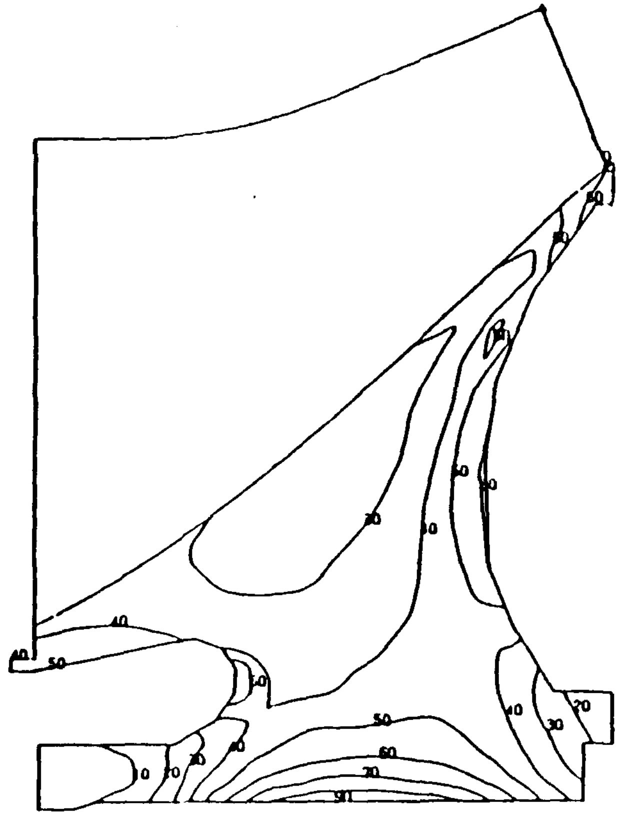


FINAL FABRIC SHAPE

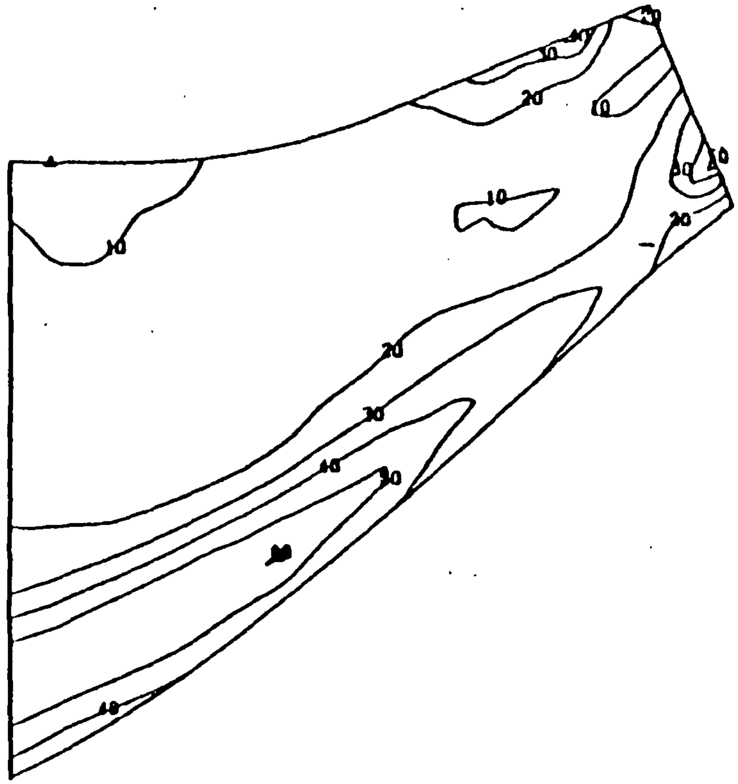


~~FIGURE 1~~

Stresses from Mixed Flow Design will Require Tailored Fiber Architectures



Disk
95 ksi max stress



Blade
61 ksi max stress

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APPENDIX E

Amercom Data for 3-D Braided SiC/SiC

Provided by AMERCOM Corporation, an Atlantic Research Corporation Company, letter to Florentine November 15, 1988.

1. Effect of Thermal Exposure in Air: Retained Stress-Strain Behavior Nicalon/SiC Composite 3-D 100/0 Braided, R-20 Coating

2. Retained Strength after Thermal Soak in Air

3. Retained Strength after Water Quench

4. Flexure Strength vs. Temperature

5. Elevated Temperature Tensile Stress - Strain Response

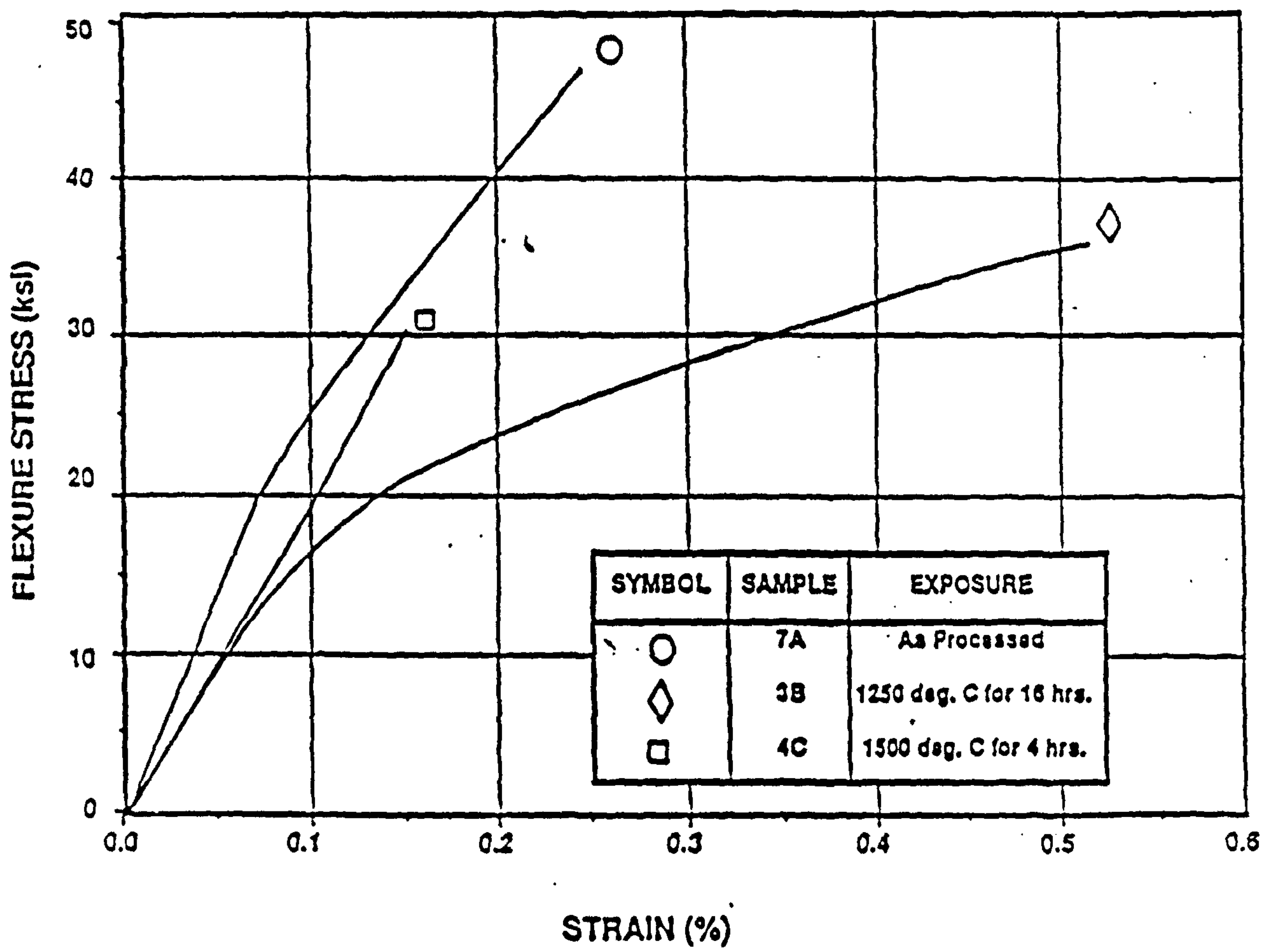
6. Initial Tensile Modulus vs. Temperature

7. Fracture Toughness - Effect of 100 Hour Heat Soak

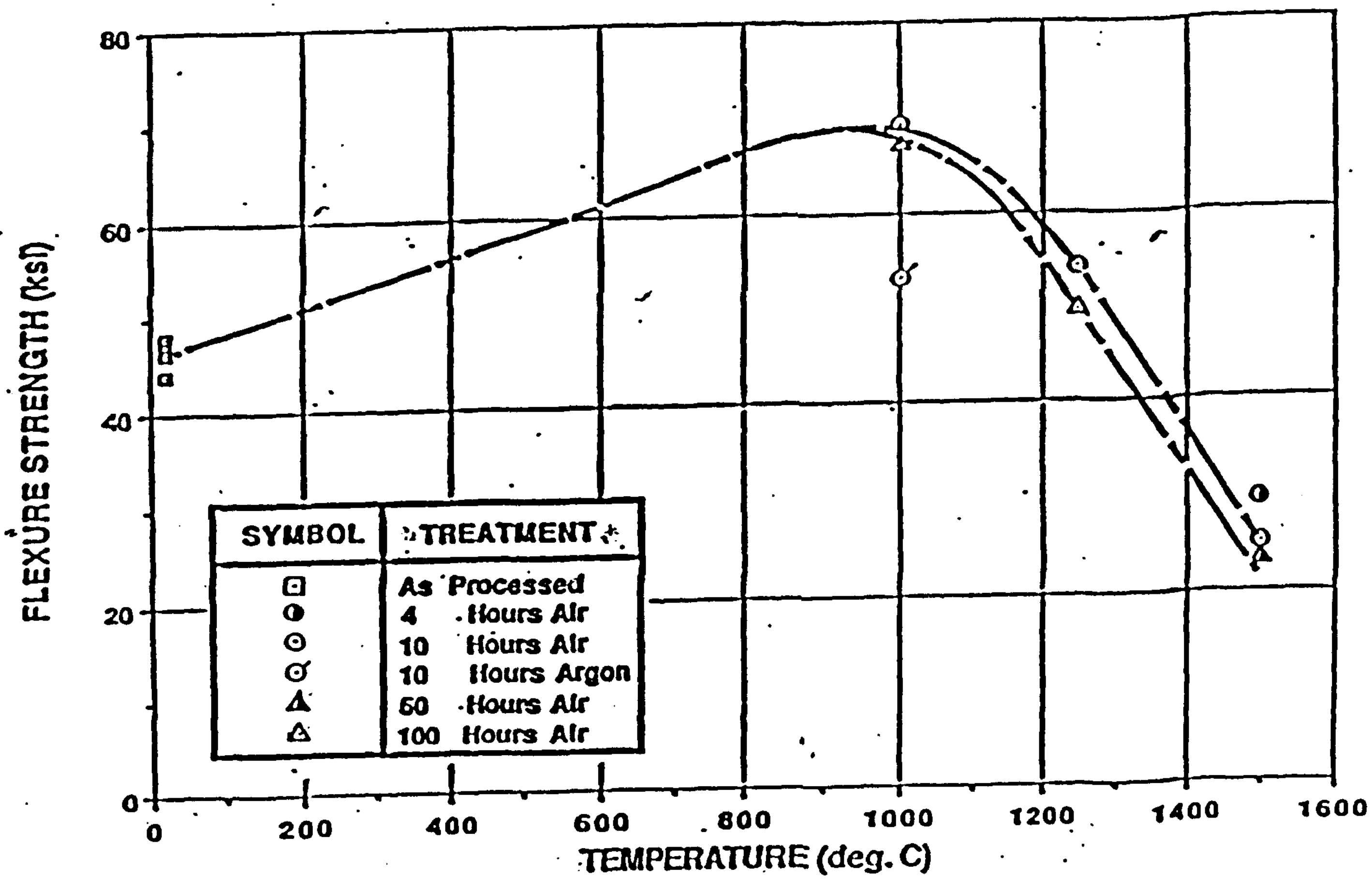
8. Comparison of Coefficient of Thermal Expansion of 3-D and 2-D Nicalon/SiC Composites

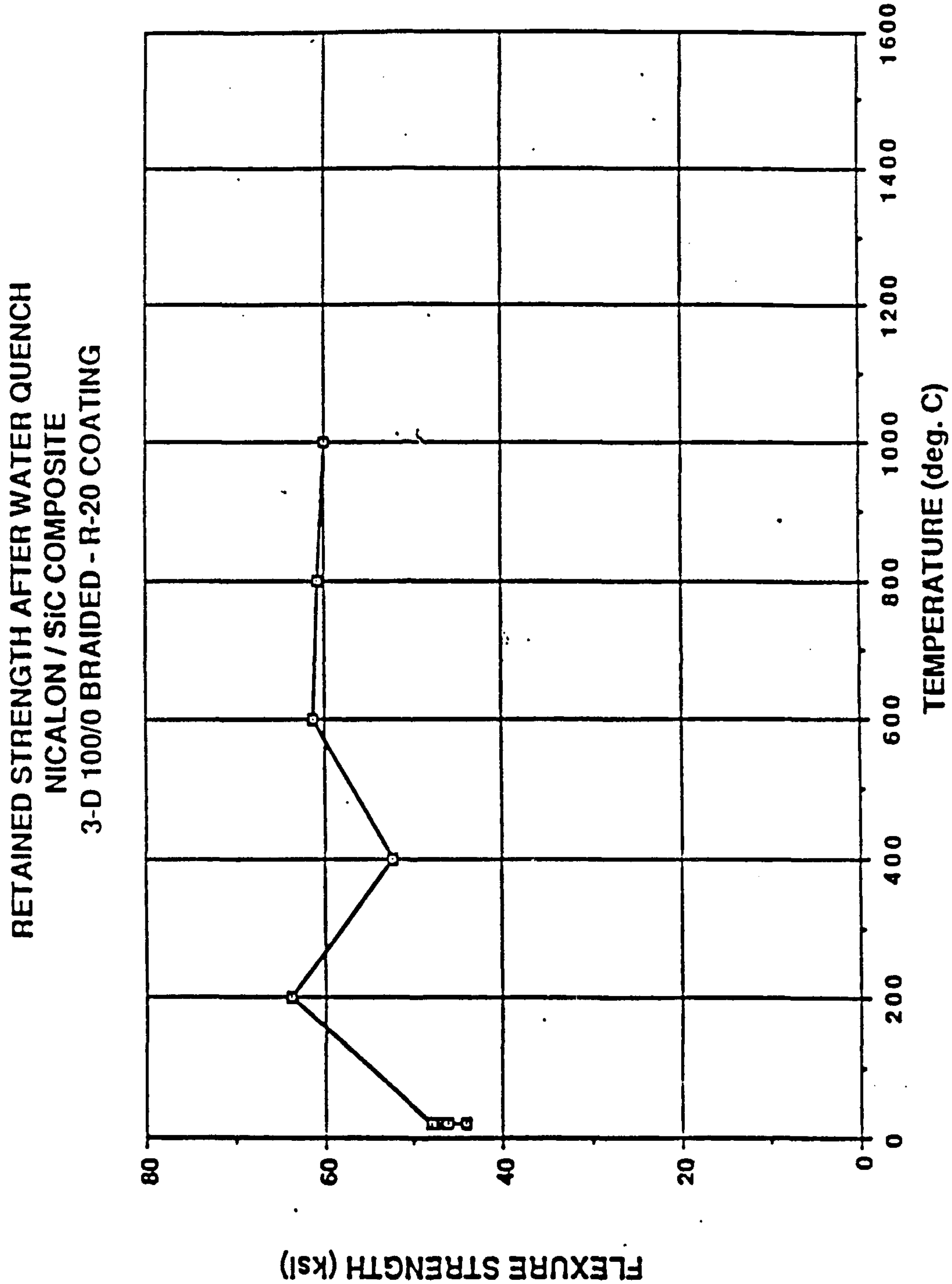
9. Thermal Diffusivity and Conductivity: 2-D Braided Nicalon/SiC Composite

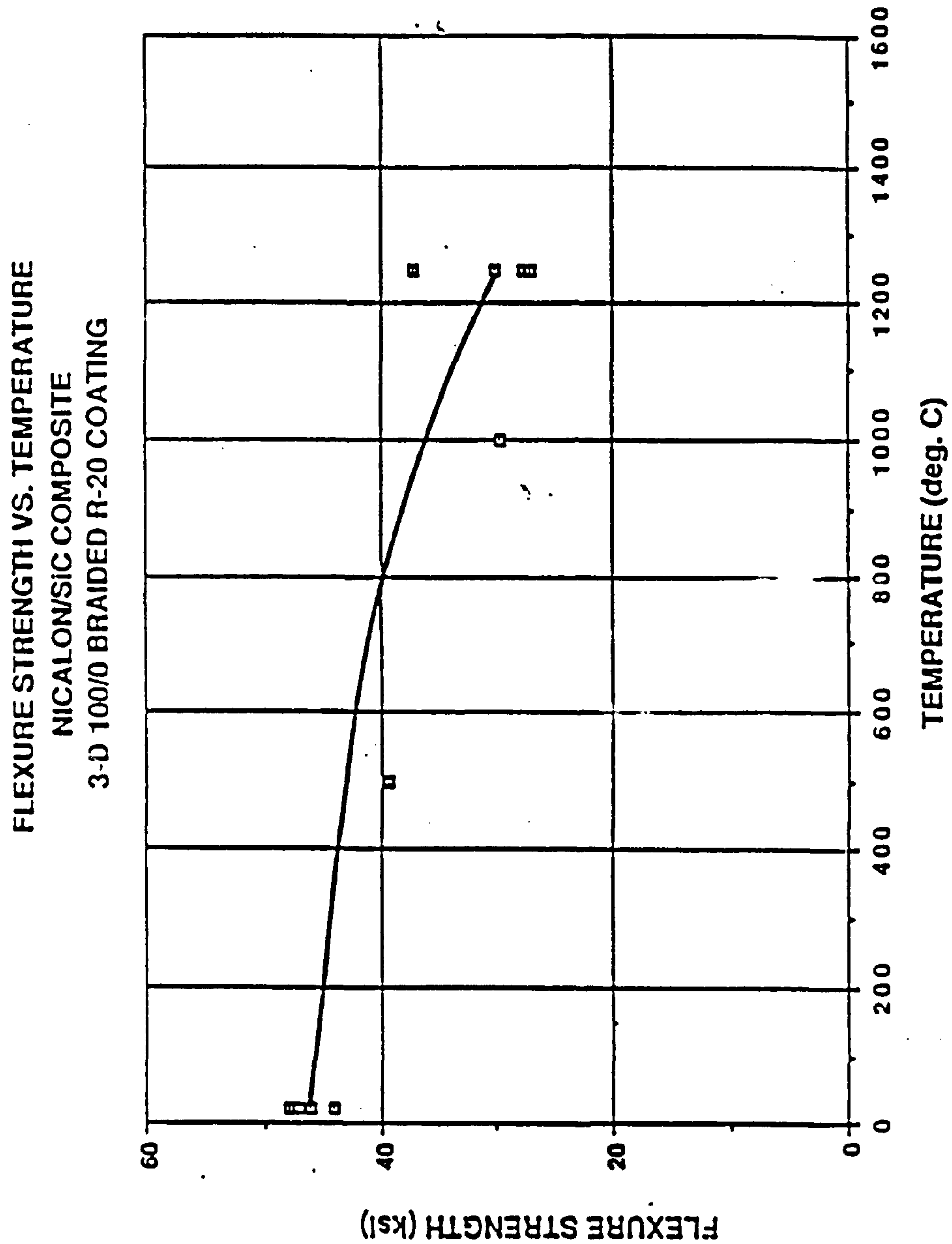
EFFECT OF THERMAL EXPOSURE IN AIR
RETAINED STRESS-STRAIN BEHAVIOUR
NICALON / SIC COMPOSITE
3-D 100/0 BRAIDED, R-20 COATING



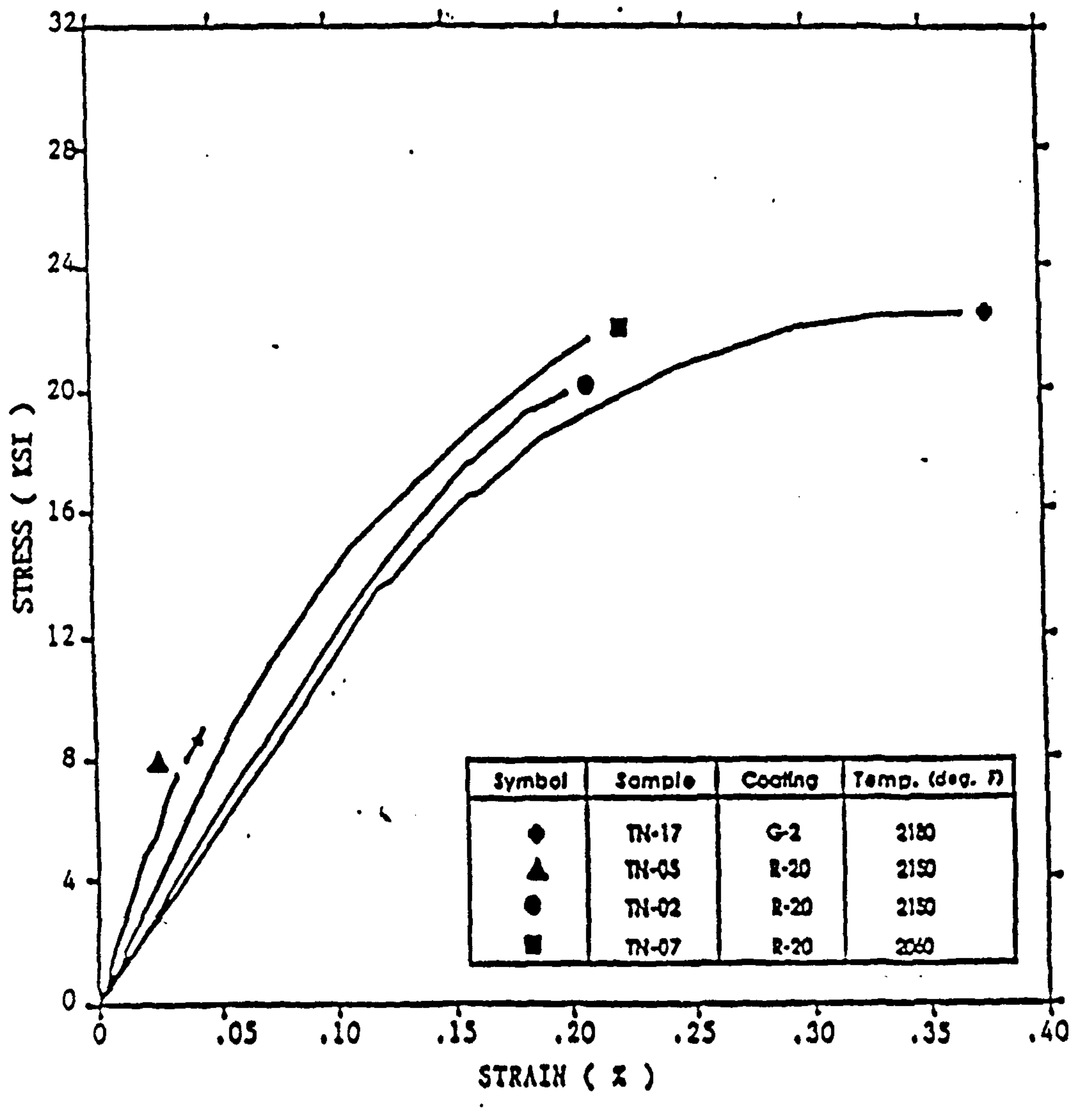
RETAINED STRENGTH AFTER THERMAL SOAK IN AIR
NICALON / SiC COMPOSITE
3-D 100/0 BRAIDED - R-20 COATING



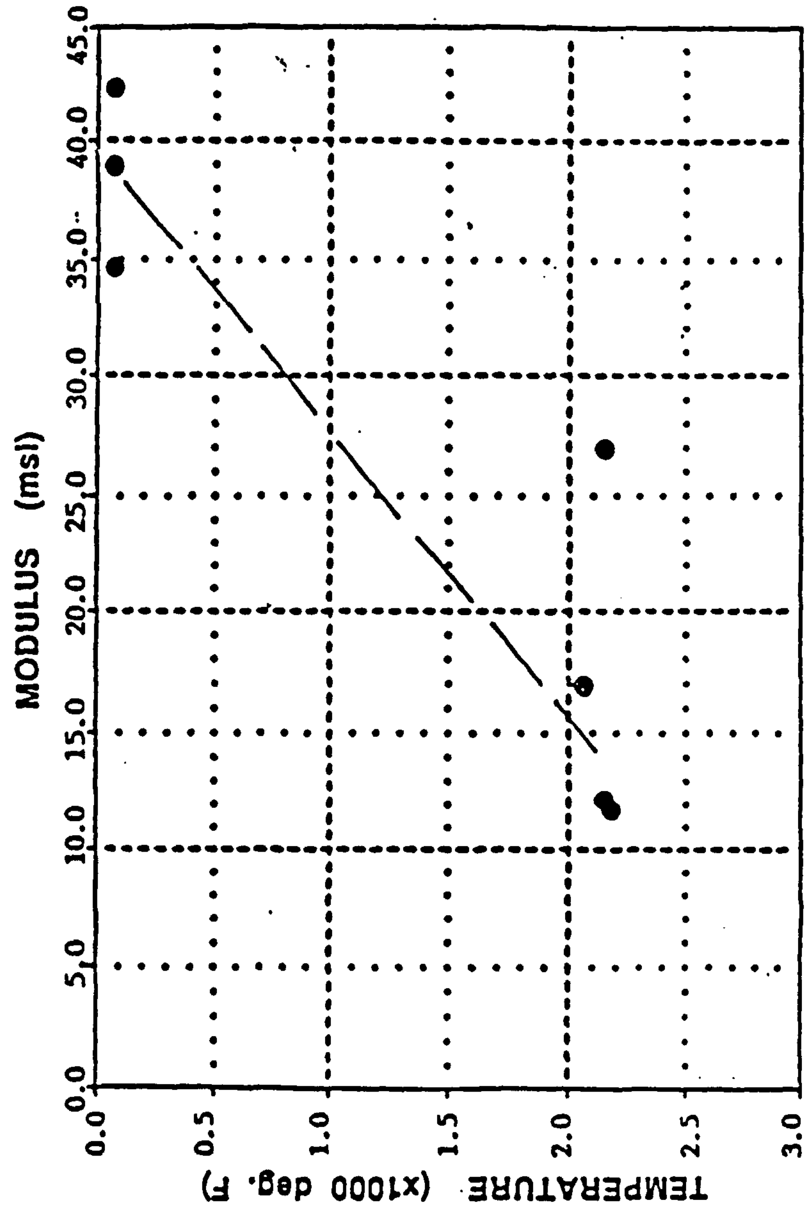

RETAINED STRENGTH AFTER WATER QUENCH
NICALON / SiC COMPOSITE
3-D 100/0 BRAIDED - R-20 COATING
FLEXURE STRENGTH (ksi)
80
60
40
20
0
TEMPERATURE (deg. C)
0
200
400
600
800
1000
1200
1400
1600


FLEXURE STRENGTH VS. TEMPERATURE
NICALON/SiC COMPOSITE
3-D 100/0 BRAIDED R-20 COATING
FLEXURE STRENGTH (ksi)
60
40
20
0
0
200
400
600
800
1000
1200
1400
1600
TEMPERATURE (deg. C)

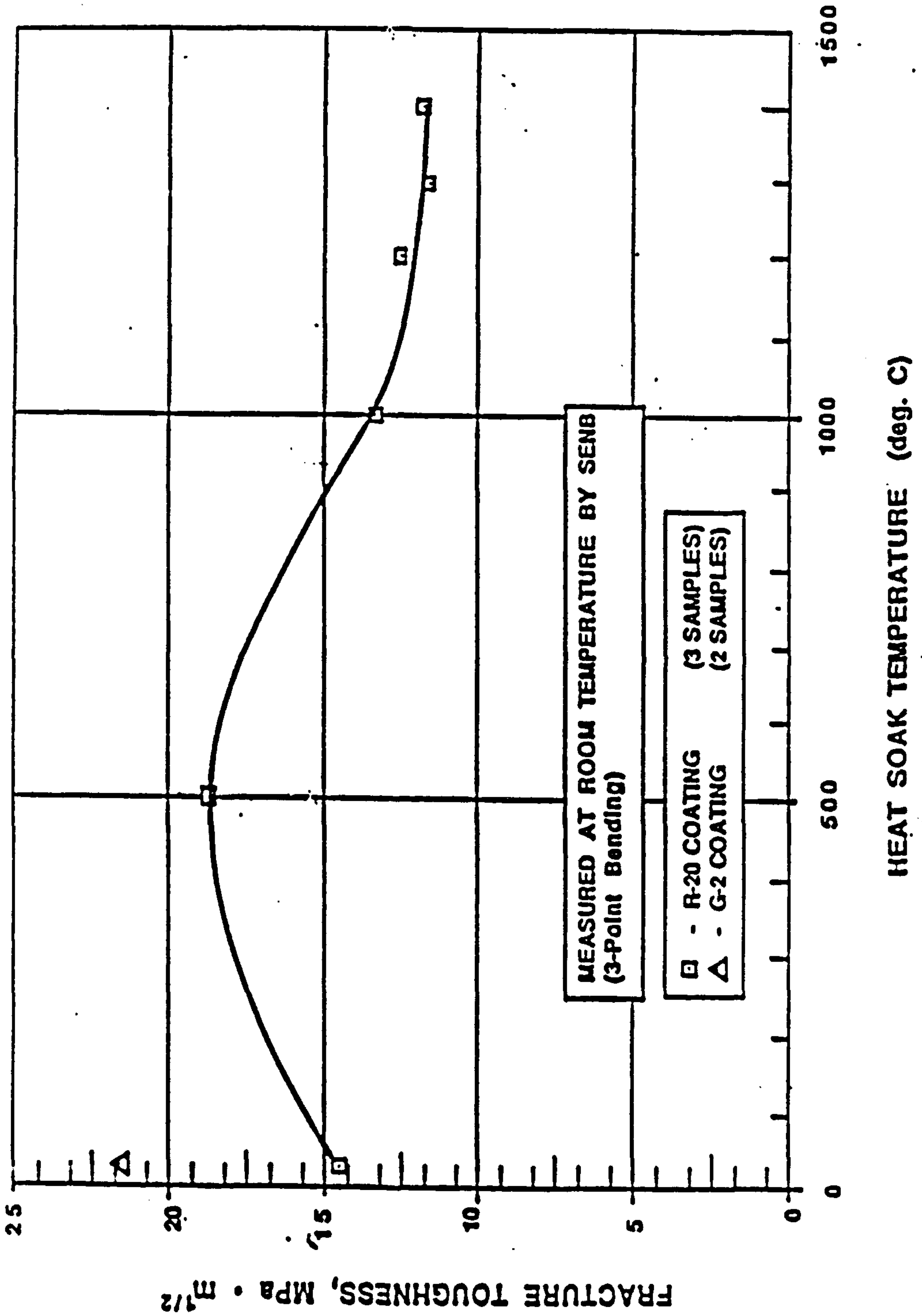
ELEVATED TEMPERATURE TENSILE STRESS - STRAIN RESPONSE.
3-D NICALON / SIC COMPOSITE

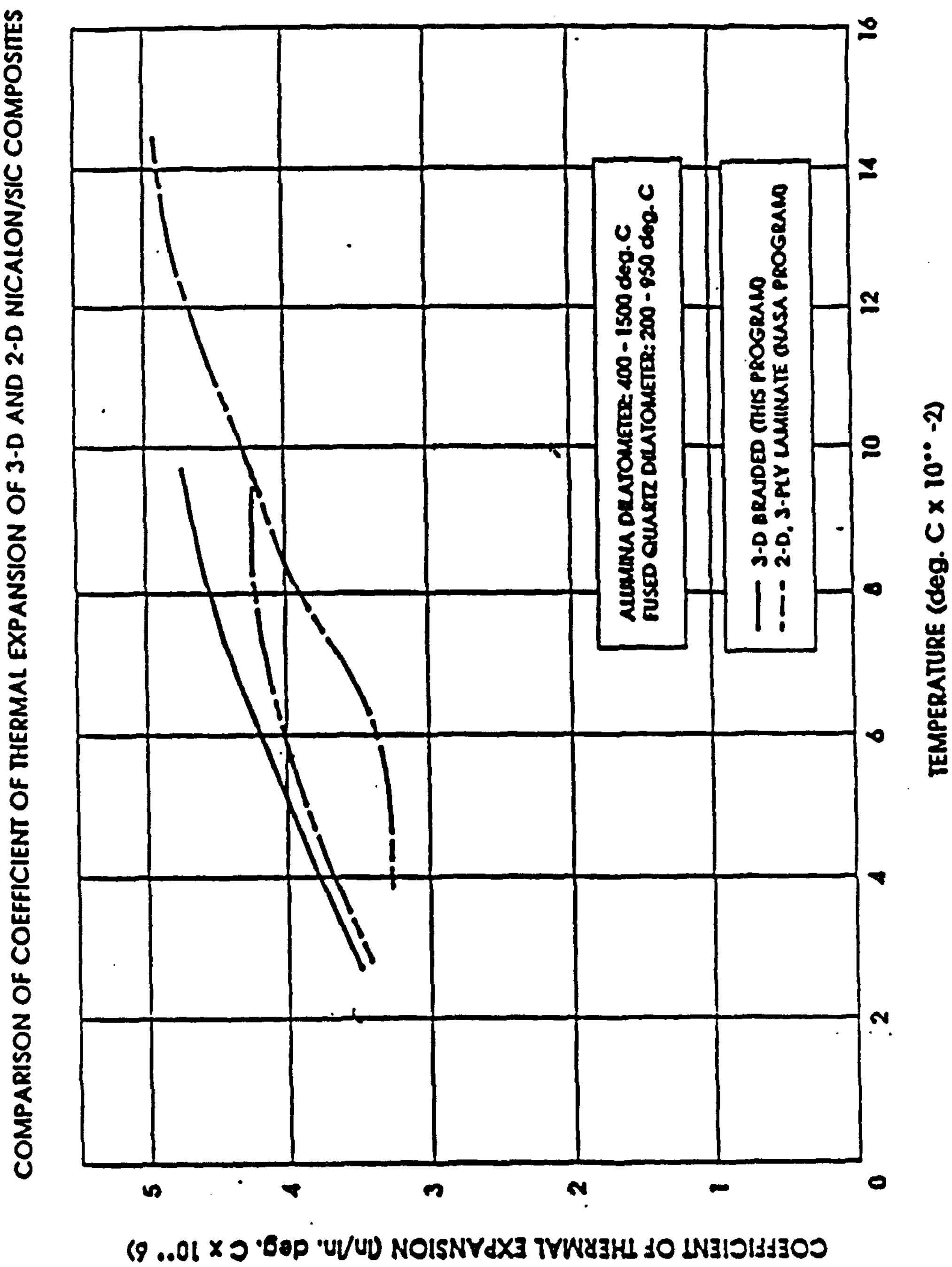


INITIAL TENSILE MODULUS vs. TEMPERATURE
3-D NICALON / SIC COMPOSITE



FRACTURE TOUGHNESS - EFFECT OF 100 HOUR HEAT SOAK
NICALON/SIC COMPOSITE
3-D 100/0 BRAIDED, R-20 COATING




COMPARISON OF COEFFICIENT OF THERMAL EXPANSION OF 3-D AND 2-D NICALON/SiC COMPOSITES
ALUMINA DILATOMETER: 400 - 1500 deg. C
FUSED QUARTZ DILATOMETER: 200 - 950 deg. C
3-D BRAIDED (THIS PROGRAM)
2-D, 3-PLY LAMINATE (NASA PROGRAM)
TEMPERATURE (deg. C x 10** -2)
COEFFICIENT OF THERMAL EXPANSION (in/in. deg. C x 10** 6)
0
2
4
6
8
10
12
14
16
1
2
3
4
5